The calculation of train stability in tornado winds

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Abstract

This paper presents a novel methodology for calculating the risk of a train overturning accident due to tornadoes. It applies a recently developed model of tornado wind fields to the complex case of a moving vehicle passing at different distances from the centre of a moving tornado. The wind speed and direction relative to the vehicle can thus be calculated. Through the use of quasi-steady force coefficients and an allowance for dynamic effects, this allows aerodynamic forces and moment time histories on the vehicle to be calculated. A parametric investigation of the effects of tornado size, strength and translational speed, and vehicle speed is then presented. A stochastic analysis methodology is then set out that allows the probability of a train overturning accident to be determined for specified statistical distributions of tornado parameters and vehicle operational parameters. It is shown that the reduction of train speed at times when tornadoes are expected would lead to a very significant reduction in accident risk. Finally the requirements for further work to refine the methodology are set out – specifically the need for statistical distributions of tornado parameters and for force and moment coefficients obtained from proper physical or numerical simulations of tornado characteristics.

Keywords – tornado, train overturning, risk analysis

1. INTRODUCTION

In recent years the wind engineering community has given increasing attention to the effects of tornadoes, and there have been a number of campaigns to attempt to measure tornado parameters in the field, e.g. [Bluestein et al, 2003: Lee and Samaras, 2004; Pietrycha et al, 2004]; a number of tornado vortex generators have been built and tested, [Haan et al, 2008; Mishra et al, 2008; Refan et al, 2014; Refan and Hangan, 2016]; and various CFD techniques have been applied to simulate tornado properties, [Ishihara et al, 2011]. In a recent paper, the authors have developed a novel analytical model of tornado wind fields and applied this to a study of the flight of wind borne debris in tornadoes [Baker and Sterling, 2017]. This analytical model is based on a solution of the high Reynolds number Navier Stokes equations and gives simple analytical expressions for the three velocity components, pressure and buoyancy flux for a range of tornado types. In a further paper [Baker and Sterling 2018] they developed this work further and produced an outline of a methodology to calculate the tornado loads on stationary structures. In the current paper, the methodology is applied to the case of a train passing through a tornado. There is some evidence that recent wind induced accidents in Japan have been caused by tornado winds [Matsui et al 2009, Suzuki et al, 2016]. Takeuchi and his co-workers [Takeuchi et al, 2008; Takeuchi and Maeda 2010] have looked at the problem, with particular regard to the dynamic overshoots of wind induced forces that might be expected to occur in the rapidly varying wind speeds observed by trains as they pass through tornadoes, and Suzuki et al (2016) have reported some preliminary model tests to measure tornado induced forces on train models as they pass through a tornado vortex generator. Japan Railways East have developed a sophisticated tornado early warning system, that uses data from a series of onshore meteorological stations and an array of Doppler Radar stations to detect tornadoes as they form over the sea, and to predict their strength and their path. If it looks as if the path will cross a railway line, appropriate operational control measures are put in place.

Section 2 sets out the wind model that will be used, based on the work of Baker and Sterling (2017), (2018) as applied to a vehicle moving through a tornado. Section 3 describes the calculation of train rolling moments for trains passing through tornadoes; investigates the effect of dynamic overshoots; and carries out a parametric investigation to understand the effect of the controlling parameters on the rolling moment time histories. Section 4 then sets out a framework for a risk analysis procedure and carries out some calculations to illustrate the methodology. Finally some concluding remarks are made in section 5.

2. TORNADO WIND FIELD

2.1 Wind field model

The tornado wind model developed by the authors in Baker and Sterling (2017) begins with the following form for radial inflow velocity U.

$$\bar{U} = \frac{-4\bar{r}\bar{z}}{(1+\bar{r}^2)(1+\bar{z}^2)} \quad (1)$$

where $\bar{U} = U/U_r$, $\bar{r} = r/r_r$ and $\bar{z} = z/z_r$ and r is the distance from the vortex centre and z is the distance above the ground, U_r is the reference radial velocity and r_r and z_r are reference values of radius and height. The radial velocity is assumed to have a maximum value (U_r) at the reference values of radius and height, which seems physically realistic and empirically models the boundary layer beneath the tornado. The reference height effectively defines the near ground tornado boundary layer where the velocity is slowed down by ground friction, and Baker and Sterling (2017) shows this is of the order of 5 to 10 m. This formulation is the simplest of those outlined in that paper and represents a simple single cell vortex with a radial inflow and an upflow around the tornado centre. The use of the continuity and circumferential momentum equation then gives the following expression for circumferential velocity V

$$\bar{V} = \frac{2.88S\bar{r}\left[\ln(1+\bar{z}^2)\right]}{(1+\bar{r}^2)} \quad (2)$$

where $\bar{V} = V/U_r$ and S is a swirl ratio (=V_{max}/U_r). This definition of the swirl ratio is different from that usually adopted for tornado vortex generators, and is based on specific tornado properties rather than the vortex generator geometric parameters. It should be noted that the absolute values of the swirl ratio as defined in this way are around three times larger than those obtained from the conventional definition. Equivalent expressions for the vertical velocity and pressure can also be derived, but they will not be used in the analysis that follows where it is assumed that the only forces on vehicles are the inertial forces due to the horizontal wind speed, and that any pressure changes as the vehicle passes through the tornado acts equally all round the vehicle. The reason for ignoring the vertical velocity component is that the force coefficients that will be used to characterise the train aerodynamic forces have been obtained from standard wind tunnel tests with no vertical velocity component. In this sense the methodology applied here is a simplified version of that adopted in Baker and Sterling (2018) where the loading on simple stationary building structures was calculated, caused by horizontal inertial forces and the differential pressure loading between the inside and outside of the structure. We further make the assumption that in what follows $\bar{z}=1$, i.e. the velocity of concern is at the top of the internal tornado boundary layer. This leads to simple expressions for the dimensionless radial and circumferential velocities that will be used in what follows.

$$\bar{U}=\frac{-2\bar{r}}{(1+\bar{r}^2)} \tag{3}$$

$$\bar{V}=\frac{2S\bar{r}}{(1+\bar{r}^2)} \tag{4}$$

Note that this formulation is for the one-cell vortex model outlined in Baker and Sterling (2017). They also present a two-cell version of this model, which inevitably is somewhat more complex algebraically. Nonetheless many tornadoes with higher swirl ratios are known to be of the two-cell type and this more complex version of the wind model could be utilised if required. For the sake of simplicity however, this paper uses only the one-cell model.

2.2 Wind field relative to a moving vehicle

We now consider the wind field relative to a moving train. Here the situation is more complex than the stationary building case considered in Baker and Sterling (2018), where both tornado and vehicle are moving. The situation being considered is sketched in figure 1. Here we assume that a tornado is travelling at a speed Q_t along the x-axis (dimensionless speed $\bar{Q}_t(=Q_t/U_r)$), and will reach the origin at a dimensionless time $\bar{t}(=tU_r/r_r)$ of zero (where t is the actual time). The vehicle is moving at a speed Q_v (dimensionless equivalent $\bar{Q}_v=Q_v/U_r$) at an angle of ϵ to the x-axis, and passes through the point (0, $\bar{Y}$) at a dimensionless time ($\bar{t}$) of zero. The situation thus modelled is of a tornado passing across the path of travel of a train with a defined closest position of the train and the tornado centre as shown in figure 1. The distance of the vehicle to the centre of the tornado is given by

$$\bar{r} = ((\bar{Y} + \bar{s}\sin(\epsilon))^2 + (\bar{s}\cos(\epsilon) - \bar{X})^2)^{0.5} \quad (5)$$

and the angle between the x-axis and the line connecting the vortex centre to the train is given by

$$\theta = \operatorname{atan}\left(\frac{\bar{Y}+\bar{s}\sin(\epsilon)}{\bar{s}\cos(\epsilon)-\bar{X}}\right) \quad (6)$$

The dimensionless distances $\bar{X}$ and $\bar{s}$ are given by

$$\bar{X} = \bar{Q}_t\bar{t} \quad (7)$$

$$\bar{s} = \bar{Q}_v\bar{t} \quad (8)$$

Referring to figure 1, the wind velocity component relative to the train in the direction of tornado movement (i.e. the abscissa) is given by $\overline{(Q}_v\cos(\epsilon) - \bar{Q}_t + |\bar{U}|\cos(\theta) + |\bar{V}|\sin(\theta))$. The first term in this expression is the wind speed relative to the train caused by train movement; the second term is caused by tornado translation, the third term is the component of the radial vortex velocity; and the fourth term is the component of the circumferential vortex velocity. Similarly the component in the direction of the ordinate is $(\bar{Q}_v\sin(\epsilon) + |\bar{U}|\sin(\theta) - |\bar{V}|\cos(\theta))$. Here of course there is no component due to tornado translation. In setting up these equations for numerical solutions, care needs to be taken over the sign of the tornado vortex velocities – the radial velocity is always directed inwards towards the tornado centre (and thus is always negative) and the circumferential velocity is always anti-clockwise.

The velocity relative to the vehicle $\mathcal{V}$, and the yaw angle ψ (the angle of the wind relative to the vehicle direction of travel) can then be calculated from

$$\bar{\mathcal{V}} = \begin{pmatrix} (\bar{Q}_v\cos(\epsilon) - \bar{Q}_t + |\bar{U}|\cos(\theta) + |\bar{V}|\sin(\theta))^2 \\ +(\bar{Q}_v\sin(\epsilon) + |\bar{U}|\sin(\theta) - |\bar{V}|\cos(\theta))^2 \end{pmatrix}^{0.5} \quad (9)$$

$$\psi = atan\left(\frac{\bar{Q}_v \sin(\epsilon)+|\bar{U}|\sin(\theta)+|\bar{V}|\cos(\theta)}{\bar{Q}_v \cos(\epsilon)-\bar{Q}_t+|\bar{U}|\cos(\theta)-|\bar{V}|\sin(\theta)}\right)-\varepsilon \tag{10}$$

where $\bar{\mathcal{V}} = \mathcal{V}/U_r$. $\bar{U}$ and $\bar{V}$ can be calculated from the tornado wind model formulation (equations (3) and (4)).

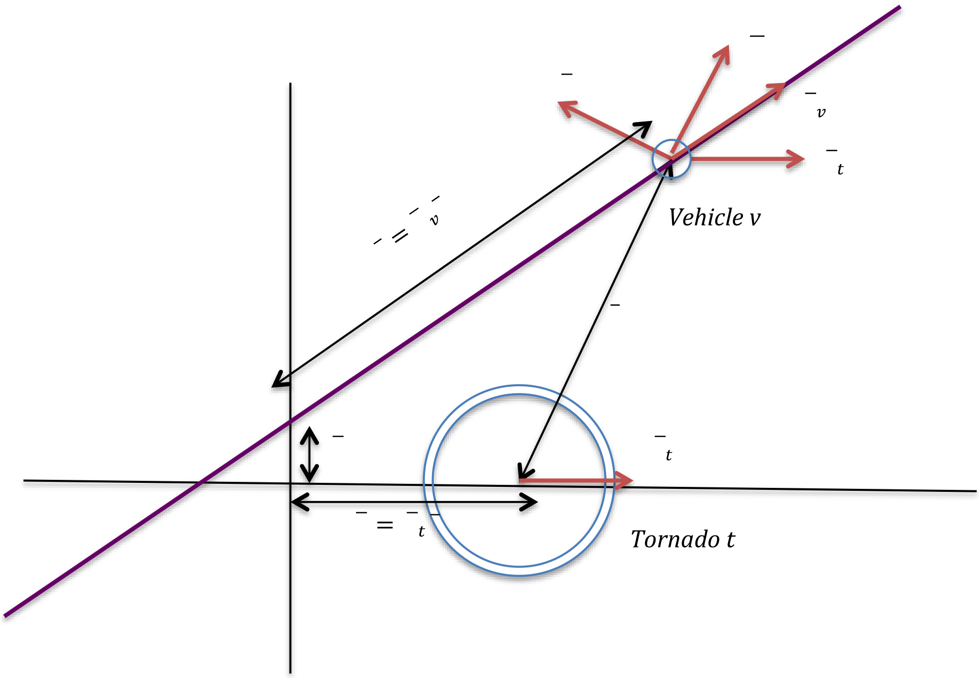


Figure 1 Vehicle moving through a tornado

3. VEHICLE OVERTURNING MOMENTS

3.1 Outline

Having obtained formulations for the magnitude and direction of the tornado velocity relative to a moving vehicle, the next step is to calculate the forces on the trains. This is normally done through the use of force coefficients. Ideally these force coefficients would be obtained from physical model of trains moving through a simulated tornado, in order to capture fully the development of the force on the train as the train moves through a highly curved and transient wind field. However there is a major problem here, as the tornadoes produced in existing tornado generators have a scale of less than 1/1000, and often much smaller (Haan et al, 2008; Refan et al, 2014), which is far too small for measuring forces on model trains where Reynolds number effects can be important - scales of around 1/25th are normally used. Indeed the scaling of tornado vortex generator flows is still a matter of some controversy - for example Gillmeier et al (2017) show that the flow structure within such generators is very dependent upon the nature and size of the generator itself. Thus in this paper we adopt a simpler approach and use force coefficients obtained from low turbulence wind tunnel tests, together with the tornado wind field relative to the train outlined in the last section and a method for specifying dynamic effects.

3.2 Force and moment coefficients

Baker (2013) produced a useful correlation of all wind tunnel force and moment coefficients test results that were available at the time he wrote, which allowed a simple generalised form for the coefficients to be determined. Now the AeroTRAIN dataset (Paradot et al, 2015) has allowed this formulation to be refined somewhat and extended to the higher yaw angle range. This data was obtained in a standard way using a large low turbulence wind tunnel with train models mounted statically on a ground plane with a representation of track and ballast. Forces and moments were measured using an underfloor balance, for Reynolds numbers greater than 2 x 10^5. Such conditions are not of course representative of tornado flows, but force data is only available from such tests. For the parameter of most practical importance, the lee rail rolling moment coefficient, at low yaw angles we have

$$C_{RL}(\psi) = \frac{R_L}{0.5\rho A h \mathcal{V}^2} = C_{RL}(30)\left(\frac{\sin(\psi)}{sin(30)}\right)^n \qquad (11)$$

and at high yaw angles

$$C_{RL}(\psi) = C_{RL}(90)\left(\frac{\sin(\psi)}{sin(90)}\right)^m \qquad (12)$$

where A is an arbitrary vehicle reference area (usually taken as 10 m^2) and h is an arbitrary reference vehicle height (usually taken as 3 m). This is a slight modification of the methodology presented in Baker (2013), with the reference values being taken at a yaw angle of 30 degrees rather than the 40 degrees used in the early paper, as this gives a somewhat better fit to the more recent data. Typical curve fits for the ICE3 train is shown in figure 2. The curve fit parameters are n = 1.5, m = -1.9, $C_{RL}(30) = 3.63$ and $C_{RL}(90) = 4.60$, and we will use these values for illustrative purposes in what follows. We will also use the following modified definition for lee rail rolling moment coefficient, based on the tornado reference wind speed.

$$\overline{C_{RL}} = \frac{R_L}{0.5\rho A {U_r}^2} = C_{RL}(\psi)\bar{\mathcal{V}}^2 \qquad (13)$$

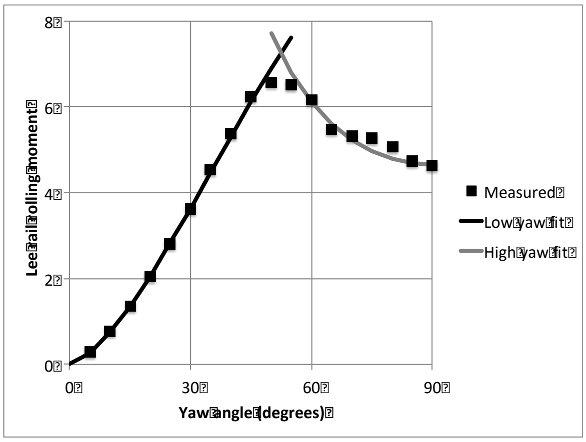


Figure 2 Rolling moment coefficient fit for ICE3 from AeroTRAIN data (low

yaw angle fit *n* = 1.5, high yaw angle fit *m* = -1.9)

3.3 Dynamic effects

Note that the coefficient values set out above were obtained from wind tunnel tests in low turbulence steady flow, and thus does not reflect the effect of tornado wind characteristics (high radius of curvature and vertical component) on the development of the flow field around the train and thus the development of the aerodynamic forces. The use of these formulae with the tornado wind speeds is thus a major approximation and effectively implies a quasi-steady approach. However the rapid accelerations as tornado winds pass over a structure or vehicle suggest there might be a dynamic overshoot of the forces on the body. Takeuchi et al (2008) carried out some low speed wind tunnel tests with rapid acceleration that did show such an overshoot. Mason and Yang (2016) considered this matter further and adapted the well know Morrison equation to investigate the relationship between quasi-static and dynamic forces on structures. In the terms of this paper, their equation can be written as

$$R_L = 0.5\rho A h \mathcal{V}^2 C_{RL} + \rho h \frac{d\mathcal{V}}{dt} C_M \forall \qquad (14)$$

where C_M is the inertial coefficient and $\forall$ is the vehicle volume. This can be written as

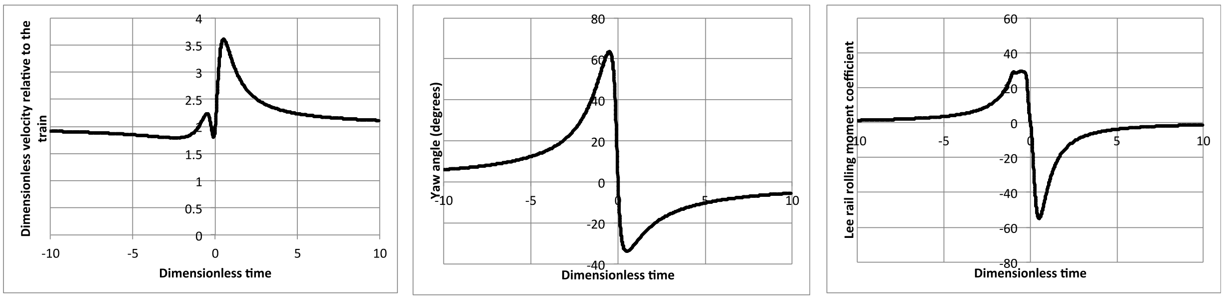
$$\overline{C_{RL}} = \bar{\mathcal{V}}^2 C_{RL}\left(1 + 2\frac{\bar{L}}{\bar{\mathcal{V}}^2}\frac{d\bar{\mathcal{V}}}{d\bar{t}}\frac{C_M}{C_{RL}}\right) \qquad (15)$$

where $\bar{L} = \frac{\forall}{A r_m}$ is a dimensionless vehicle parameter. The term in brackets is the dynamic multiplier, which is proportional to the acceleration of the velocity relative to the vehicle. It effectively represents the force required to accelerate a volume of air of the same volume as the train. Applying this methodology to typical buildings suggested that for the downbursts considered in Mason and Yang (2016), then dynamic effects are likely to be small, but the variations in wind speed observed by moving vehicles are very rapid indeed, and some investigation of the importance of such dynamic effects for the situation under consideration here is required.

3.4 Vehicle moment time histories

We now consider some results from the analysis outlined above. We begin with the very simple case of a stationary tornado centred at the origin ($\bar{Q}_t = 0$), with the vehicle travelling along the *x*-axis ($\bar{Y}$=0, ε=0). The dimensionless train speed $\bar{Q}_v = 2$ and the swirl ratio S =2, are taken as typical realistic values of these parameters and the rolling moment coefficient is given by the quasi-steady value with the parameter values as given above. Note that, as there is a factor of around 3 between the values of swirl ratio used here and the conventional values, this value of the swirl ratio is within the accepted one cell vortex range. The results for dimensionless wind speed relative to the vehicle yaw angle and side force coefficient (without applying the dynamic magnification of equations (14) and (15)) are shown in figure 3. It can be seen that there are major variations in all three parameters as the vehicle passes through the tornado. The wind velocity relative to the train increases to a peak at a dimensionless time of 0.5, and the yaw angle has a positive peak before the train passes through the tornado, and then the flow direction rapidly changes and a negative peak can be seen as the train emerges from the tornado. The flattening of the side force coefficient characteristic between dimensionless times of -1 and -0.4 reflects the fact that the yaw angle has moved from the low range to the high range (at an angle of 52 degrees), and thus the force coefficient characteristic has changed. Figures 4a and 4b show the value of the dynamic multiplier, for the ratio of the inertial to rolling moment coefficients of 2.0 (which is probably rather higher than in reality) and a dimensionless vehicle parameter of 0.2, and the effect that this has on the force coefficient. This can be seen to be small, due to the fact that the dynamic magnification factor only differs significantly from unity near the centre of the vortex when the speeds are low.

Figure 5 shows the results of a brief parametric study of the effects of vehicle and tornado speeds, swirl ratio and proximity of the tornado to the train on the rolling moment coefficients, with the base case for the study being that used in the above calculations. The dynamic effect is included. From figure 5a, it can be seen that the faster the train speed, the more rapidly the lee rail rolling moment coefficient changes, which would be expected as the train moves more rapidly through the tornado core. Similarly, as the tornado speed increases in the direction of travel of the train, the moment coefficients fall as would be expected (figure 5b). The effect of increasing tornado swirl ratio can be seen to be very significant (figure 5c – note the change of scale on the graph). Note here that the higher values of swirl ratio are probably somewhat above the one cell vortex range, and thus the model is not strictly applicable. The effect of the vehicle moving away from the tornado centre (figure 5d) is complex with the negative peak being reduced in magnitude and the positive peak being increased as $\bar{Y}$ goes from 0 to 0.5 and then decreasing as $\bar{Y}$ goes to 1.0.

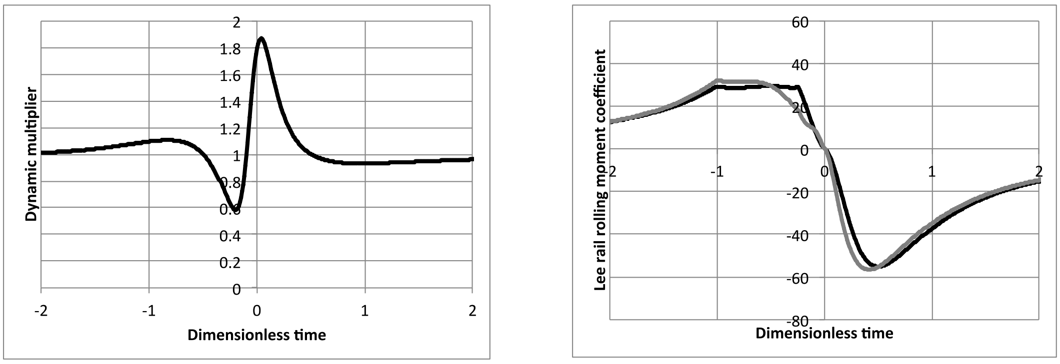


a) Velocity relative to the train

b) Yaw angle

c) Lee rail rolling moment coefficient

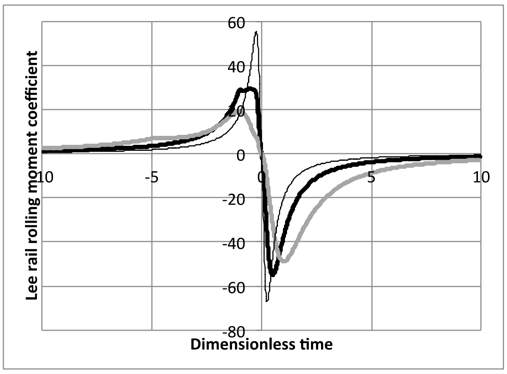
Figure 3 Train travelling along x axis passing through stationary tornado at the origin ($\bar{Q}_v = 2$, $\bar{Q}_t = 0$, S=2, $\bar{Y}$=0, ε=0)



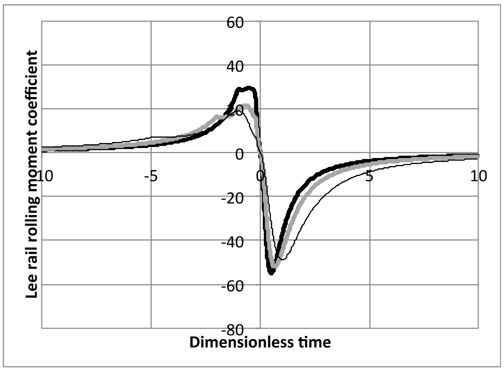
a) Dynamic multiplier

b) Dynamic effects on rolling moment coefficient (black line – no correction; grey line – with correction)

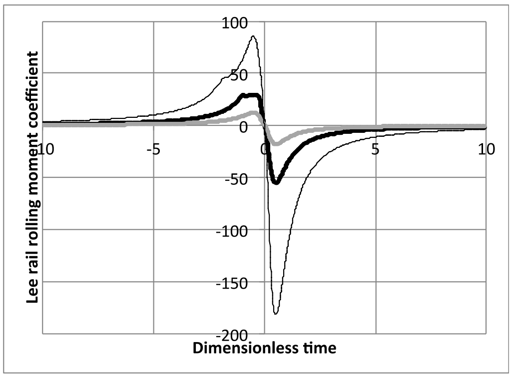
Figure 4. Effect of applying dynamic multiplier ($\bar{Q}_v = 2$, $\bar{Q}_t = 0$, S=2, $\bar{Y}$=0, ε=0)



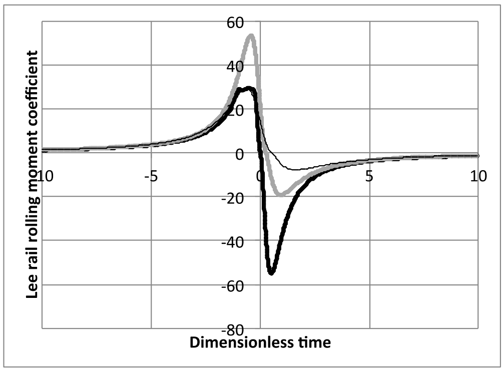
a) Effects of varying train speed (grey line $\bar{Q}_v$ = 1; black line $\bar{Q}_v$ = 2; thin black line $\bar{Q}_v$ =4)



b) Effects of varying tornado speed (black line $\bar{Q}_t$= 0; grey line $\bar{Q}_t$ = 0.5; thin black line $\bar{Q}_t$ =1)



c) Effects of varying swirl ratio (grey line *S*= 1; black line *S* = 2; thin black line *S*=4)



d) Effects of varying proximity (black line *Y*= 0; grey line *Y*= 0.5; thin black line *Y*=1)

Figure 5 Parametric analysis around $\bar{Q}_t = 0$, $\bar{Q}_v = 2$, *S*=2, $\bar{Y}$=0, *ε*=0

4. APPLICATION OF METHODOOGY

4.1 Possible applications

The wind velocity magnitude and direction and the lee rail rolling moment coefficients calculated in sections 2 and 3 have the potential to be used in a number of ways as follows.

- As a tool in train certification - a series of design tornadoes could be developed as input to analytical spring / mass / damper multi degree of freedom MDOF models of train suspension dynamics to assess the tornado wind speeds at which a train would overturn, in a manner that is similar to the application of the Chinese Hat gust profile in the current CEN methodology (CEN, 2010).
- To help determine train restriction strategies during tornado periods – for a particular site an envelope of tornado strength and swirl ratio could be developed for which overturning will occur, and warning / train restriction systems activated when dangerous conditions are forecast to occur.
- To carry out a full risk analysis of a particular train overturning on a particular route.

The next section will describe the latter in more detail.

4.2 Risk analysis

The calculation of moment coefficient time histories is of course only the first step in calculating the risk of an accident. An accident will occur if the windward wheel reaction falls to some specified value (zero or some percentage of its normal level). Clearly whether or not this occurs depends upon the nature of the tornado itself (size and strength), the relative speeds and directions of travel of the train and the tornado, and how close the train comes to the tornado centre. The tornado characteristics are of course statistical variables. Thus in developing a risk analysis we follow the approach taken by Baker and Sterling (2018) in the calculation of tornado wind loads on structures, and illustrated in figure 6. In essence this calculates the risk of a train, travelling at a specific speed, overturning on a specific section of track. The tornado parameters are specified statistically, which is in principle possible from observations of tornado strength and size, and the moment coefficient time histories calculated for a large number of statistical realisations. For each realisation or tornado parameters the calculated maximum rolling moment is compared with the restoring moment due to the weight of the train, and an incident taken to occur if the windward wheel reactions are less than 10% of their fully loaded value. Thus the probability of incidents occurring in the ensemble of realisations can be determined. This probability is then convoluted with the probability that a tornado will actually occur within the vicinity of the track section (which can be obtained, in principle at least, from tornado climatological studies), and the probability that a train is in the section (from train operating characteristics), to give the probability of an incident in that section. Note that the probabilities of tornadoes occurring in any one kilometre square are very small, and quantitative data for such probabilities is only available in a few areas of the world – in the USA, Japan, and, for lower strength tornadoes, in the UK (Simmons et al (2011), Tamura et al (2015), Kirk (2014) In making these calculations we assume that the effects of the train suspension are not taken into account in the wheel unloading calculation, although these could be included if it were felt desirable to do so. Note that this methodology has similarities to that used in Romalic et al (2016) for the calculation of tornado risk on static structures, which also looks at the vulnerability and consequences of tornado damage, but does not model tornado loads to the same level of detail as in this paper.

As an example, we consider a hypothetical vehicle, with the lee rail rolling moment characteristics as given in the last section, a mass of 50,000 kg moving at a specified speed of on a 1km stretch of track of gauge 1.5 m. We assume, following Dotzek et al (2003), that the tornado wind speed probability distribution is given by the Weibull distribution. The CDF of this distribution is

$$P_{\Omega} = e^{-\left(\frac{\Omega}{\lambda}\right)^{k}} \quad (16)$$

where P_Ω is the probability that, given the occurrence of a tornado, the maximum wind speed in the tornado will be less than $\Omega\left(=\left(U_r{}^2+V_{max}{}^2\right)^{0.5}\right)$. λ and *k* are the Weibull parameters. Dotzek et al (2003) gives values of these parameters for a range of different geographical locations. Unfortunately this work was based on a now outdated version of the Fujita scale and the analysis needs to be reworked somewhat to update the values that are given. In what follows, for illustrative purposes, we use $\lambda = 40$ m/s and *k*= *4* (figure 7). Further the work of Tamura et al (2015) allows the variation of tornado core radius and translational velocity to be related directly to Ω. Thus in what follows we will use the following relationships

$$r_m = 1.20\ \Omega \tag{17}$$

$$Q_t = 0.22\ \Omega \tag{18}$$

The dimensional nature of equation (17) is unsatisfactory, but again will suffice for the purpose of illustrating the method. Finally we assume the following correlation of the swirl ratio with the maximum velocity.

$$\mathrm{S} = 0.3 + 0.00075\ \Omega^2 \tag{19}$$

This equation is loosely based on the work of Kosiba and Wurman (2010) who analysed the Spencer, South Dakota tornado from 1998, and the vortex generator results of Refan et al (2014), with the values of swirl ratio they obtained being converted into the definition used in this paper. The results of the latter suggest that swirl ratio increases with tornado velocities. This approach thus involves very many assumptions, and again it is best to regard equation (19), which is again dimensional in nature, as a very approximate form, for illustrative purposes only. The reference radial velocity U_r can then be obtained from

$$U_r = \frac{\Omega}{(1+S^2)^{0.5}} \tag{20}$$

Thus r_M, Q_t, S and U_r are all assumed to be uniquely related to the maximum tornado velocity, with the same probability distribution. This can only be a major simplification of reality. We further assume that a tornado passes through a 1 km square area centred on the centre of the track, at an arbitrary angle. $\bar{Y}_0$ is taken to be uniformly distributed between -500 m and +500 m, and ε uniformly distributed between 0 and 90 degrees. 5,000 individual realisations were calculated, and the cumulative distribution function of overturning moments is shown in figure 8 for a typical high-speed train operational speed of 80 m/s, and reduced speeds of 40 m/s and 0 m/s (stationary), together with the restoring moment due to the mass of the train. Note that the probabilities shown in this graph do not take into account the probability that a tornado will be present (which needs to come from a study of tornado climatology) or the probability that the train will actually be in the section (which needs to be derived from operational characteristics). If we consider the 80 m/s curve, the graph shows that, if there is a tornado in the 1 km square, there is a 34% chance of the critical rolling moment value being exceeded. It can be seen that the lowering of train speed results in a significant reduction in the probability that the rolling moment will exceed the restoring moment (by a factor of 15 between train speeds of 80 m/s and 0 m/s), and represents a viable way of reducing risk. This probability can then be used in assessing the consequences of an accident, and the need, or otherwise, to undertake mitigation measures.

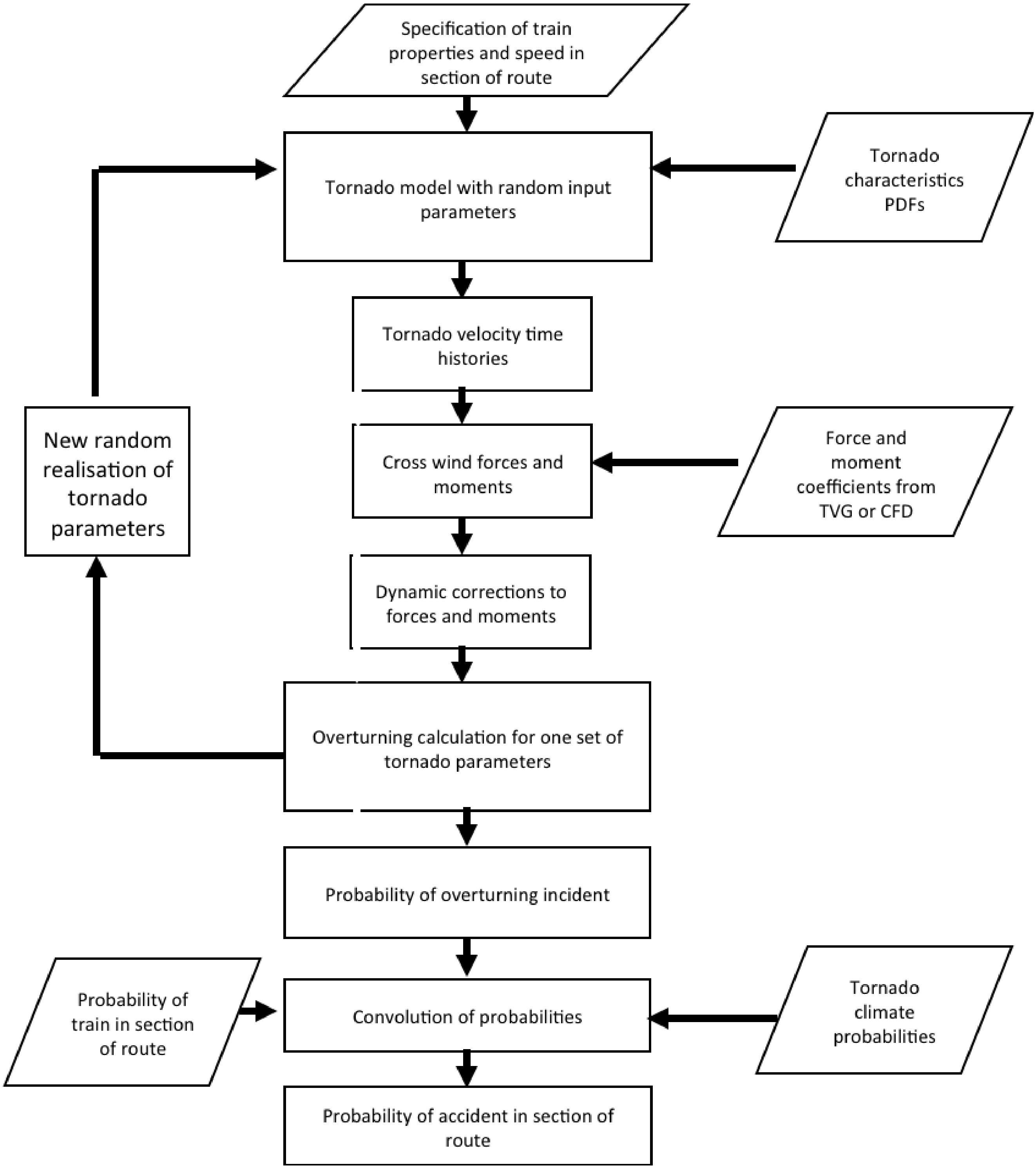


Figure 6 Risk calculation procedure

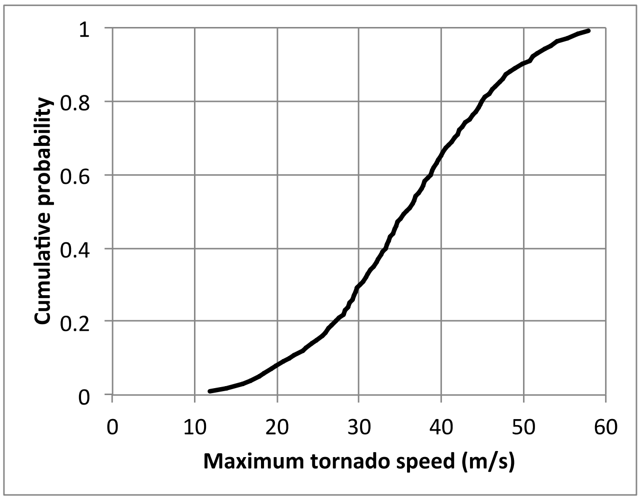


Figure 7 Cumulative probability distribution for maximum tornado wind speed

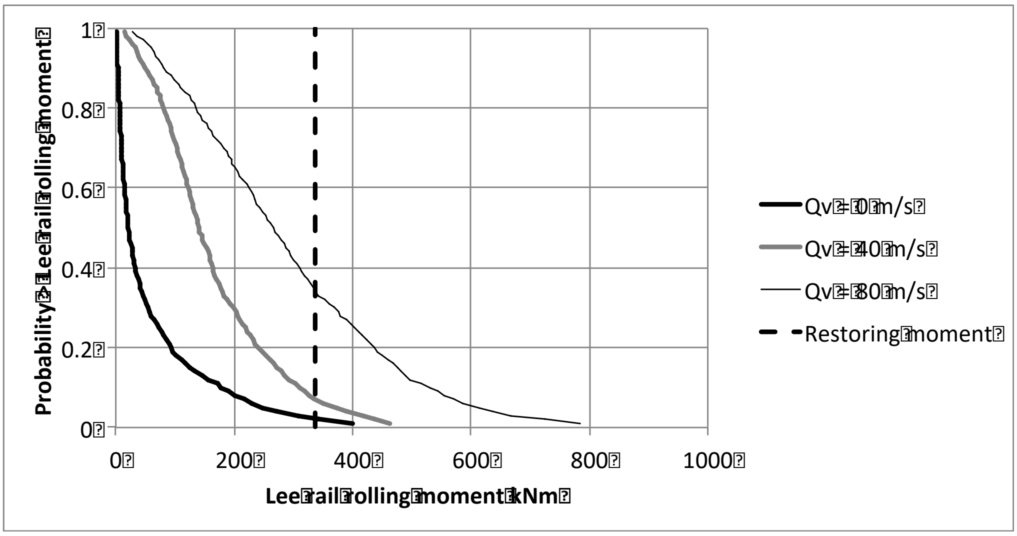


Figure 8 Cumulative probability distribution for overturning moment

5. CONCLUDING REMARKS

This paper has presented a novel outline analysis of the calculation of the tornado wind field seen by a moving train, the development of the wind induced forces on the train and the calculation of the risk of a train overturning whilst passing through a tornado. The analysis has the following components.

- The use of a recently developed wind speed model applied to a moving vehicle passing through a translating tornado.
- A formulation of the tornado induced wind forces on trains that includes an allowance for dynamic effects.
- The inclusion of tornado characteristics in a risk framework model that allows for the risk of a tornado induced overturning accident to be calculated.

The method has been shown to be viable, and has potential to be used in a variety of ways. Although the results must be regarded as provisional, the effect of reducing train speed on the overturning probabilities is clear and indicates that this might prove to be a viable and practical method of alleviating accident risk.

These points being made however, further work in the following areas is required before the method can be used routinely.

- The inclusion of a two-cell tornado model to allow for the variation in the form of the tornado as tornado strength increases –this can be based upon the work of Baker and Sterling (2017).
- Rolling moment coefficient data is required that has been obtained in model tests or CFD simulations of tornado like winds.
- For any particular site information is required of tornado climatology and the distribution of tornado characteristics, to refine the correlations used for radius, translational speed and swirl ratio with tornado maximum velocity.

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