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Abstract

High-sided vehicles are particularly vulnerable to high wind conditions and at sites that are regarded as vulnerable a range of vehicle restrictions are imposed in high winds. These may include vehicle speed reductions or complete restrictions on the movement of different categories of vehicle at different wind gust speeds. This paper builds on earlier work that has been carried out, and seeks to develop a simple but conservative method that can be used to specify vehicle restriction strategies. This is based on a collation of a wide range of data for aerodynamic rolling moment coefficients that allows a simple parameteristaion to be developed. This is then used in an overturning model to develop a non-dimensional relationship between overturning gust speed and vehicle speed. The parameter used in the non-dimensionalisation is a characteristic wind speed that is a function of vehicle weight and geometry and effectively specifies the vulnerability of the vehicle to overturning in high winds. Dimensional relationships between overturning gust velocities and vehicle velocities can thus be derived for different vehicle types, and used to develop site-specific vehicle restriction methods.

Notation

A	Reference area (m^2)
c	Characteristic velocity (m/s) – equation 7
$C_{RL}(30)$	Lee wheel rolling moment coefficient at $\psi = 30$ degrees
$C_{RL}(\psi)$	Lee wheel rolling moment coefficient at ψ degrees
h	Reference height (m)
H	Vehicle height (m)
L	Vehicle length (m)
M	Vehicle mass (kg)
p	Wheel base semi-width (m)
R_L	Lee wheel rolling moment (Nm)
u	Wind gust velocity (m/s)
u_i	Wind gust velocity at which overturning occurs (m/s)
$\bar{u}$	u/c
$\bar{u}_i$	u_i/c
v	Vehicle velocity (m/s)
$\bar{v}$	v/c
V	Wind velocity relative to vehicle (equation 3) (m/s)
$\bar{V}$	V/c
α	Proportion of wheel unloading
β	Wind direction relative to vehicle direction of travel (°)
ψ	Yaw angle (equation 4)(°)
ρ	Density of air (kg/m^3)

Keywords

Bridges, Design methods and aids, Risk and Probability Analysis, Transport management, Transport planning, Viaducts, Wind loading and aerodynamics

1. Background

High-sided road vehicles, particularly when unladen, are prone to overturning in high winds, and there are frequent news reports of such accidents (eg BBC 2015, 2017a, 2017b). Safety considerations thus often make it necessary to place restrictions on the movement of road traffic during wind storms, at sites such as long span bridges or on exposed embankment sites. These restrictions can take the form of speed limits for different types of vehicle, or for the complete closure of the road to vehicles of all types. For example on the Queensferry Bridge in Scotland (which we will consider further later in this paper), a blanket speed restriction of 40mph is put into place when the wind gusts above 50mph (22.4m/s); double deck buses are not allowed to travel over the bridge for gust speeds higher than 60mph (26.8m/s); high sided vehicles are banned from crossing when wind gust speeds exceed 70mph (31.3m/s), all traffic except cars are stopped for gusts above 90mph (40.3m/s) and the bridge is closed when gust speeds reach 100mph (44.7m/s) (Forth Bridges, 2018). Similarly, restrictions on vehicle movement can sometimes be required in urban areas, where the ground level wind speeds around high-rise buildings can be sufficient to cause vehicle overturning accidents (BBC, 2014).

There have been a number of investigations of the effects of cross winds on road vehicles in the past. Clearly the most basic information that is required is a knowledge of the cross wind forces and moments on vehicles. Wind tunnel measurements of these forces for a variety of different vehicle types are reported in Baker (1988), Coleman and Baker (1990), Sterling et al (2010), Cheli et al (2011a,b), Dorigati et al (2012), Han et al (2014) and Liu et al (2016). Data is given for vehicles on flat ground, bridge, embankment and viaduct scenarios. In addition Haan et al (2017) report measurements on vehicle forces in a Tornado Vortex Generator and Xiang et al (2017) describe measurements made using a moving model facility. More recently CFD calculations of cross wind forces have been made - see Sterling et al (2010) and Stoyanoff et al (2015) for example. As is the case in most sectors of wind engineering, full-scale data with which to compare the wind tunnel and CFD measurements are understandably sparse and the only investigations of this type known to the author are those of Sterling et al (2010) for a stationary vehicle.

At this point, it should also be noted that a number of tests have also been carried out to investigate the transient wind effects on vehicles as they pass bridge pylons – see Aregntini et al (2011), Rocchi et al (2012) and Wang and Xu (2015). This particular issue is beyond the scope of the method presented here and will not be addressed further in what follows.

The crosswind forces having thus been obtained, some method is required to translate these forces into a wind speed level that will result in an accident. Methods for such a procedure were first derived by the author in the 1980s using simple static analytical models of vehicle behaviour, with and without human driving input. (Baker 1986, 1987 and 1991), and gave critical wind conditions for vehicle sideslip and rollover accidents. Snaebjornsson et al (2007) put the analysis into a probabilistic framework which enables an accident index to be defined, for certain levels of accident probability. This approach has been taken further and refined somewhat by Batista and Perkovic (2014), and Kim et al (2016) use the latter's methodology to calculate the risk of a wind induced accident on a long span bridge. Cheli et al (2006) used a more complex dynamic vehicle / driver model of the vehicle and its suspension in simulated fluctuating wind conditions to evaluate vehicle forces and path. This approach is further developed in the investigations of Zhou and Chen (2015) and Chen et al (2015) who both describe a complex calculation linking the fluctuating wind conditions, the dynamic behaviour of vehicles, and the dynamic behaviour of bridges. Finally mention should be made of the work of Maruyama and Yamazaki (2006) who use a more complex version of the original static analysis, and interestingly incorporated human driver behaviour through inputting the crosswind model into a driver simulator, thus introducing real human involvement.

On many long span bridges and other exposed sites, wind barriers of different sorts are used to protect traffic from high winds and to increase the wind gust speeds when traffic restrictions are put into place. These barriers are usually designed using wind tunnel tests and the level of shelter is usually quantified by a reduction in the forces and moments on the vehicle, for example Chu et al (2013), Dorigati et al (2014), Chen et al (2015) and Alonso-Estebanez et al (2017). These force and moment measurements are not always related to the values of wind speed that may result in accidents and to the risk of such accidents.

Ultimately the problem that arises when applying the results of the above research is that the real life situation at any one site is complex, with a wide range of different vehicle types, sizes, weights and levels of vulnerability, with wind approaching from a range of directions and many of the methods outlined above (including those of the author) are practically difficult and time consuming to use. Operationally any traffic restrictions need to be quite simple and easy to implement, and must be aimed at protecting the most vulnerable types of traffic at the site. Complex methodologies are thus not always easy to use in practical situations, although they can be useful in calibrating simpler methods. In addition it will be seen from what follows that there can be considerable uncertainty in the aerodynamic forces and moments, with large differences between the results of nominally similar wind tunnel tests or CFD calculations. This paper thus in some ways steps back from recent developments in the field and sets out a methodology for assessing safe wind speeds for vehicles in high cross winds that, whilst as rigorous as possible, is deliberately simple and in a form that can be used easily by bridge operators and transport authorities, both in the planning and design stage for new infrastructure and operationally when considering whether restrictions need to be applied. The methodology is outlined in section 2, and the specification of aerodynamic force and moment coefficients considered in section 3. An analysis that relates these coefficients to accident wind speeds is given in section 4, and the application of this analysis set out in section 5. Section 6 considers how this methodology can be used in wider contexts of risk assessment, and some concluding remarks are made in section 7.

2. Outline of methodology

The methodology that is adopted is as follows.

- Only the most common and serious type of wind-induced accident is considered – the rollover of large vans, lorries and other similar vehicles. Such events dominate the accident statistics – see for example the description of the 1991 Burns Nights storm in the UK (Baker and Reynolds, 1991) where this type of overturning incident accounts for 47% of all injury accidents. Sideslip accidents, where vehicles were blow to one side without overturning, only contributed to around 19% of the total number of accidents. Most of the other accidents involved vehicles colliding with trees or other debris blown onto the road. Thus of the accidents directly caused by strong winds, around 70% are of the rollover type.
- Accidents are assumed to occur when the vertical reaction at the windward wheels becomes zero, and the vehicle is assumed to overturn as a solid body.
- The wind speeds that result in such accidents are fully specified by a one to three second gust speed.
- Data for the aerodynamic parameter of relevance to this situation, the rolling moment about the leeward wheels is collated from a range of investigations, and a simple parameterisation is suggested that is a reasonable and largely conservative representation of the experimental results.
- A simple rollover analysis is set out that allows a non-dimensional crosswind characteristic function to be determined - non-dimensional overturning wind speed as a function of wind direction and non-dimensional vehicle speed.
- The non-dimensionalisation of velocities is carried out through the use of a characteristic velocity, which defines the rollover characteristics of the vehicle.

- Both non-dimensionalised and dimensional curves of accident wind speed against vehicle velocity can then be determined which can be used to specify vehicle and wind speed restrictions at specific sites.

3. Overturning moment coefficients

The overturning moment on a vehicle about the leeward wheels, R_L, can be specified by the overturning moment coefficient C_{RL}

$$C_{RL} = \frac{R_L}{0.5\rho A h V^2} \quad (1)$$

where A is a reference area and h is a reference height, ρ is the density of air and V is the wind velocity relative to the vehicle. Rolling moment coefficients are usually measured from static wind tunnel tests, as a function of yaw angle ψ, (the wind angle relative to the vehicle), although other sorts of physical model test (Tornado Vortex Generators or Moving Models) have been used, as have CFD calculations and, to a very limited degree, full scale tests. A collation of data from a range of experiments for flat ground and unobstructed bridge scenarios is given in figure 1, plotted in the form of $C_{RL}(\psi)/C_{RL}(30)$ where $C_{RL}(30)$ is the rolling moment coefficient at a yaw angle of 30 degrees. This curve includes data from most of the investigations outlined in section 1, although potentially useful data from the work of Han et al (2014) and Liu et al (2016) could not be used because not all the relevant dimensions of the vehicles are given. It can be seen that the data collapses tolerably well when plotted in this way, at least in the lower yaw angle range, and can be conservatively represented by the simple curve

$$\frac{C_{RL}(\psi)}{C_{RL}(30)} = \frac{\sin(\psi)}{\sin(30)} \quad (2)$$

This is a slight modification of the method used by Baker (2013) for cross wind forces on trains, where the reference yaw angle was taken as 40 degrees, and a rather more complex curve fit used. Note that the values for most of the experiments diverge from the simple curve for yaw angles of greater than 50 degrees, with the main exception being the results of the full-scale experiments of Sterling et al (2010) – the filled grey triangles. The author would argue that primacy should be given to such results, which represent some sort of ground truth, and thus the simple curve of equation 2, which is a reasonable representation of these results, is appropriate. Nonetheless this full-scale data has much scatter that is not apparent from the results shown, but which again suggests a simple, conservative approach is appropriate.

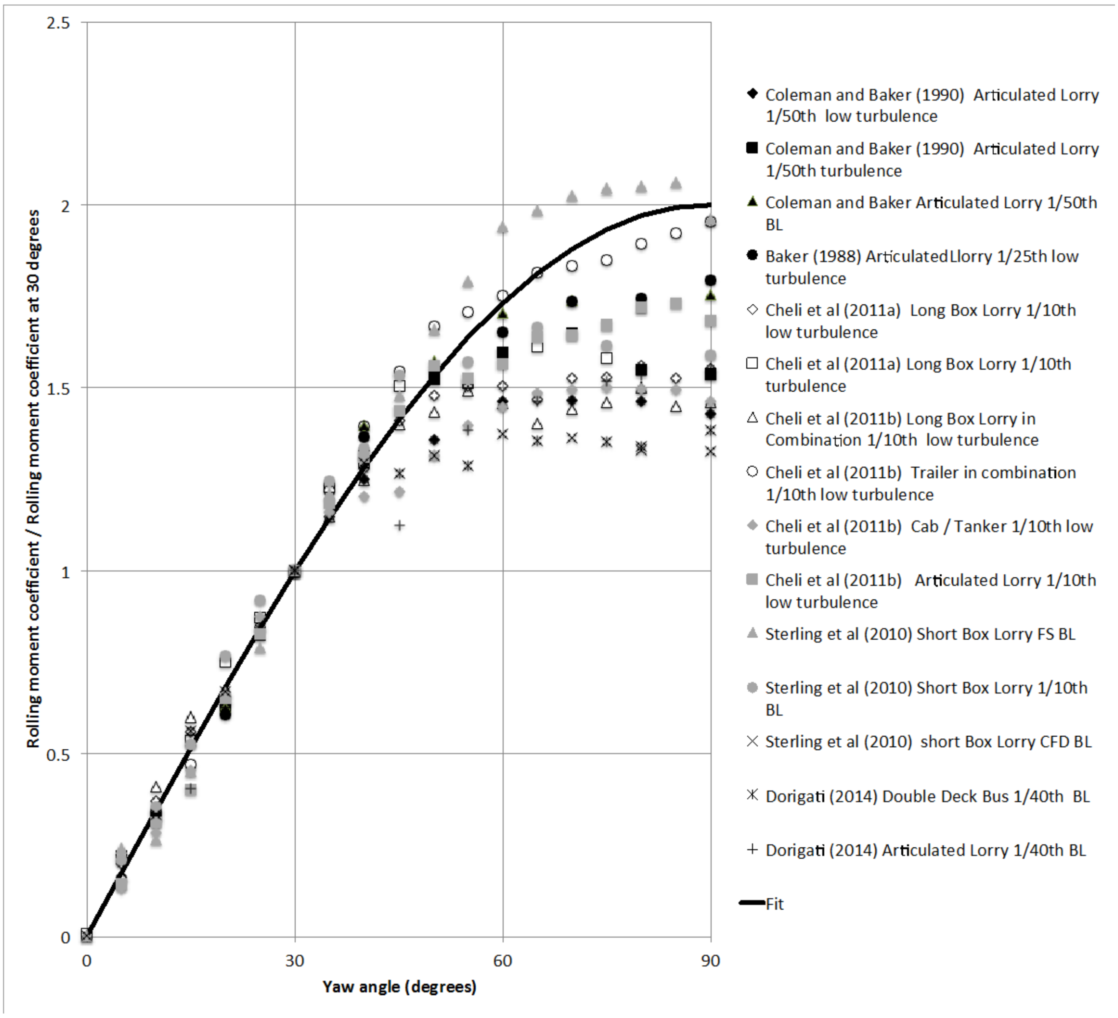


Figure 1 Collation of leeward wheel rolling moment characteristic data

(Articulated Lorry –cab with container or box on trailer; Short Box Lorry – rigid, two or three axle; Long Box Lorry – Rigid – four or more axles; Cab / Tanker – cab articulated with tanker trailer; Double Deck Bus – High bus with two floors)

Author	Vehicle type	Simulation	L (m)	H (m)	$C_{RL}(30)$ with A=10m^2 and h = 3m	$C_{RL}(30)$ with A=LH and h = H
Baker (1988)	Articulated Lorry	LT, 1/25th	13.5	3.8	3.39	0.52
Coleman and Baker (1990)	Articulated Lorry	LT, 1/50th	13.5	3.8	2.63	0.41
		HT, 1/50th			2.81	0.43
		BL, 1/50th			3.31	0.51
Sterling et al (2010)	Short Box Lorry	BL, FS	6	3.5	0.75	0.31
		BL, 1/10th			0.96	0.39
		BL, CFD			0.94	0.38
Cheli et al (2011a)	Long Box Lorry	LT, 1/10th	7.8	3.5	1.15	0.36
		HT, 1/10th			1.21	0.38
Cheli et al (2011b)	Long Box Lorry combination with Trailer	LT, 1/10th	7.8	3.5	1.23	0.39
	Trailer combination with Long Box Lorry	LT, 1/10th	7.6	4	1.38	0.34
	Cab / Tanker	LT, 1/10th	14.0	3.7	1.27	0.20
	Articulated Lorry	LT, 1/10th	14.0	3.8	2.16	0.31
Dorigati et al (2014)	Double Deck Bus	BL, 1/40th	10.1	4.4	2.80	0.43
	Articulated Lorry	BL, 1/40th	16.6	3.8	3.15	0.48

Table 1 Collation of leeward wheel rolling moment coefficient data

(LT – turbulence simulation, HT – high turbulence simulation, BL – boundary layer simulation)

The values of the rolling moment coefficients at a yaw angle of 30 degrees are given in table 1. Two values of the coefficient are give, the first based on values of A and h of 10m^2 and 3m respectively (which are conventional, nominal values) and the second based on values of A given by the product of the overall vehicle length L and overall vehicle height H, and values of h given directly by H. The first values show a steady increase of the coefficient with the length of the vehicle as would be expected, for all the sharp edged vehicles, but with the Cab / Tanker value (without sharp edges in the cross section) having a lower value than would be expected for its length. Again, with exception of the Cab / Tanker, the second set of values are almost all within the range of 0.3 to 0.5, with the values for the Short Box Lorry being in the range 0.31 to 0.38; for the

Long Box Lorry in the range 0.36 to 0.39 and for the Articulated Lorry being between 0.41 and 0.52, with the exception of the results of Cheli (2011b) which lie significantly below this range. These ranges indicate the level of uncertainty that attached to any estimation of rolling moment coefficients obtained experimentally or computationally.

4. Accident wind speed calculation

From the velocity vector diagram of figure 2a, it can be seen that If a vehicle is moving at a velocity v with a crosswind of velocity u at a direction β to the direction of travel, then the wind velocity relative to the vehicle V is given by

$$V^2 = ((ucos(\beta) + v)^2 + (usin(\beta))^2) \quad (3)$$

The wind direction relative to the vehicle, the yaw angle ψ, is given by

$$\tan(\psi) = \frac{u \sin(\beta)}{u\ cos(\beta)+v} \quad (4)$$

Now if one assumes that the critical condition occurs when the windward wheel reaction falls to zero, a simple static analysis (figure 2b) gives the expression.

$$C_{RL}(0.5\rho AhV^2) = Mgp \quad (5)$$

where M is the vehicle mass and p is the semi-wheel base. In practice a certain proportion α of wheel unloading (say 0.9) is often taken as the critical condition, giving the modified expression

$$C_{RL}(0.5\rho AhV^2) = \alpha Mgp$$

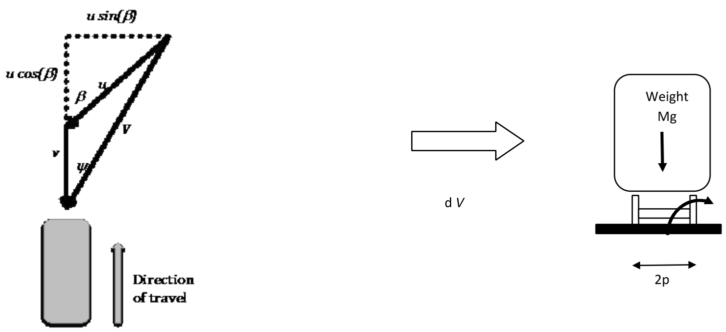
α may also be interpreted as a parameter that represents the dynamic effects of vehicle suspension in the overturning process, or simply as a safety factor. From the above expressions it is possible to derive the following dimensionless relationship.

$$\left(\bar{v}^2 + \bar{u}_i^2 + 2\bar{u}_i\bar{v}cos(\beta)\right)(\bar{u}_i\sin(\beta))^2 = 1 \quad (6)$$

where $\bar{v} = v/c$ and $\bar{u}_i = u_i/c$, u_i is the wind velocity where and overturning incident will occur and c is the characteristic velocity given by

$$c = \sqrt{\frac{\alpha Mgp}{\rho C_{RL}(30)Ah}} \quad (7)$$

This expression in equation (6) gives the relationship between the dimensionless crosswind speed for an overturning incident to occur, the wind direction and the dimensionless vehicle speed, with the vehicle parameters being fully specified by the characteristic velocity. It is completely general and can be applied to all vehicles and situations where the assumptions set out in section 2 apply. It is also very simple in form, although can only be solved analytically for very specific cases. This will be seen to be its major utility.



(a) Velocity vectors (b) Static model

Figure 2 Velocities and rolling moments

5. Application of methodology

Figure 3 shows the variation of the normalised overturning wind speed $\overline{u_i}$ with wind direction β for a variety of normalised vehicle speeds $\bar{v}$. It can be seen that the curves show a minimum value for values of $\overline{u_i}$ between 70 and 90 degrees. Note that the curve for zero velocity has a minimum value of 1.0 at β = 90 degrees i.e. a pure cross flow. In these conditions $u_i = c$, and thus the characteristic velocity can be interpreted as the accident gust speed for a stationary vehicle normal to the wind direction. Figure 4 shows the variation of this minimum value with normalised vehicle speed. This gives normalised accident wind speeds against vehicle speeds, which are appropriate to situations where the wind direction is very variable or unknown, and thus the minimum value is the appropriate value to use. Curves are also given for values of $\overline{u_i}$ at wind directions of 30, 60 and 90 degrees, which may be useful if the wind direction can be more accurately specified. It can be seen that there is little difference between the curve for minimum values and those for wind directions of 60 and 90 degrees, although the 30 degree curve is significantly higher, and it will be seen below that, if the wind direction can be confidently predicted to be along the vehicle direction of travel, wind speed and vehicle speed restrictions could be relaxed.

The curve for the minimum values in figure 4 can be given to a good approximation by the very simple expression

$$\overline{u_i} = e^{-\left(\frac{\bar{v}}{2.4}\right)^{1.41}} \quad (8)$$

and that for the 30 degree wind direction case by the equally simple expression

$$\overline{u_i} = 1.41e^{-\left(\frac{\bar{v}}{3}\right)^{1.05}} \quad (9)$$

These formulae are wholly empirical curve fits and have no physical meaning, but their Weibull-like forms are somewhat satisfying for wind engineering practitioners.

The above analysis has been expressed in dimensionless terms, and as such can give generalised formulae applicable to a range of situations. In practical terms however it is useful to express the results in dimensional terms. To do this values of the characteristic velocity c are required. Typical values of this parameter are given in table 2 for a small number of vehicle categories where aerodynamic information is available. Representative values of the weights and dimensions are assumed. It can be seen that for unladen vehicles the values are between 30m/s and 40m/s, with the laden values being very much higher. Figure 5 thus shows the variation of the minimum value of the overturning wind speed for all wind directions against vehicle speed for values of c of 30, 35 and 40m/s. In both cases the units used for speed are miles per hour, which is of course scientifically non-standard, but are the units actually used in practice in the UK and USA. Also shown are the vehicle restriction limits for Queensferry Bridge in Scotland outlined in section 1, although only those for double deck buses and high-sided vehicles are relevant to the current methodology (section 1). These limits ensure that the $c = 30$m/s line and $c = 35$m/s lines are not crossed by buses and high sided vehicles respectively, which seems very sensible in the light of the values of c given in table 2. The analysis and the operational experience of this particular bridge are thus in reasonable agreement.

Finally figure 6 shows the wind speeds for vehicle overturning for the minimum values and the minimum values for wind directions of less than 30 degrees to the vehicle direction of travel. The latter can be seen to be significantly higher than the former, showing the potential for relaxing wind and vehicle speed limits if the wind direction is known to be predominantly along the roadway.

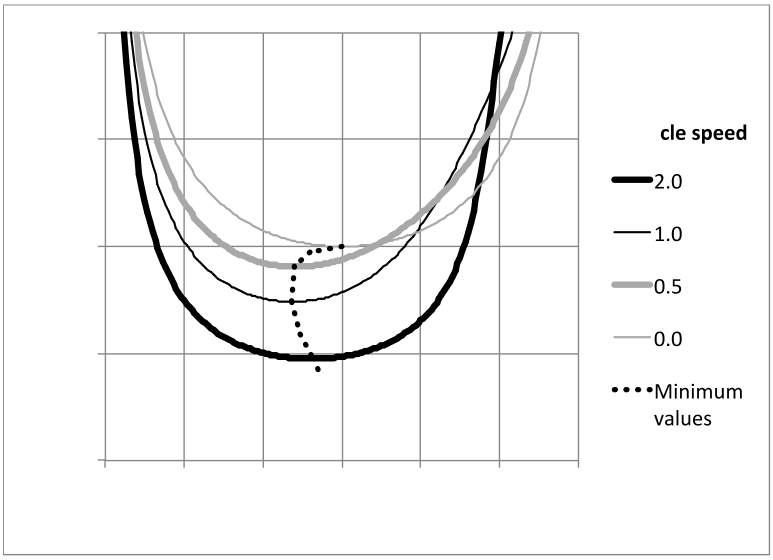


Figure 3. Non-dimensional accident wind speeds against wind direction for a range of non-dimensional vehicle velocities

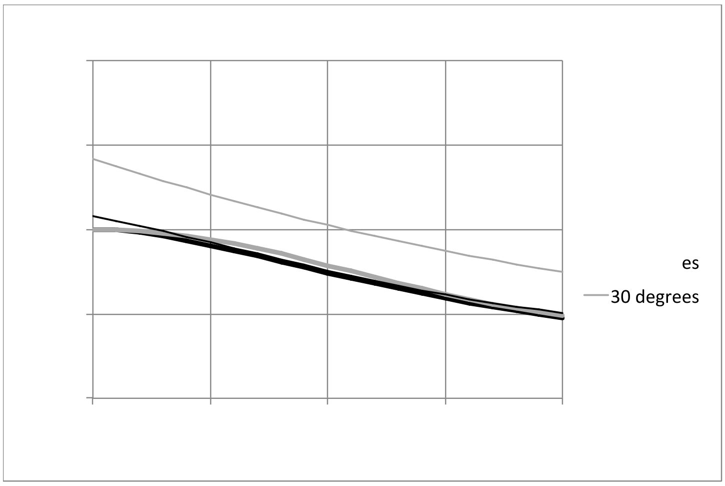


Figure 4. Values of non-dimensional accident wind speeds against non-dimensional vehicle velocities for the minimum values and different wind direction values.

	Unladen mass *M* (kg)	Laden mass *M* (kg)	*L* (m)	*H* (m)	*p* (m)	$C_{RL}(30)$	Unladen *c* (m/s)	Laden *c* (m/s)
Small Box lorry	7000	16000	8.0	3.5	1.2	0.4	40.2	60.8
Large Box Lorry	9000	18000	12.0	3.5	1.2	0.4	37.2	52.7
Articulated lorry	16000	40000	15.0	4.0	1.2	0.5	34.3	54.2
Double Deck Bus	10000	14000	12.0	4.4	1.2	0.4	29.7	35.2

Table 2 Calculation of characteristic velocities

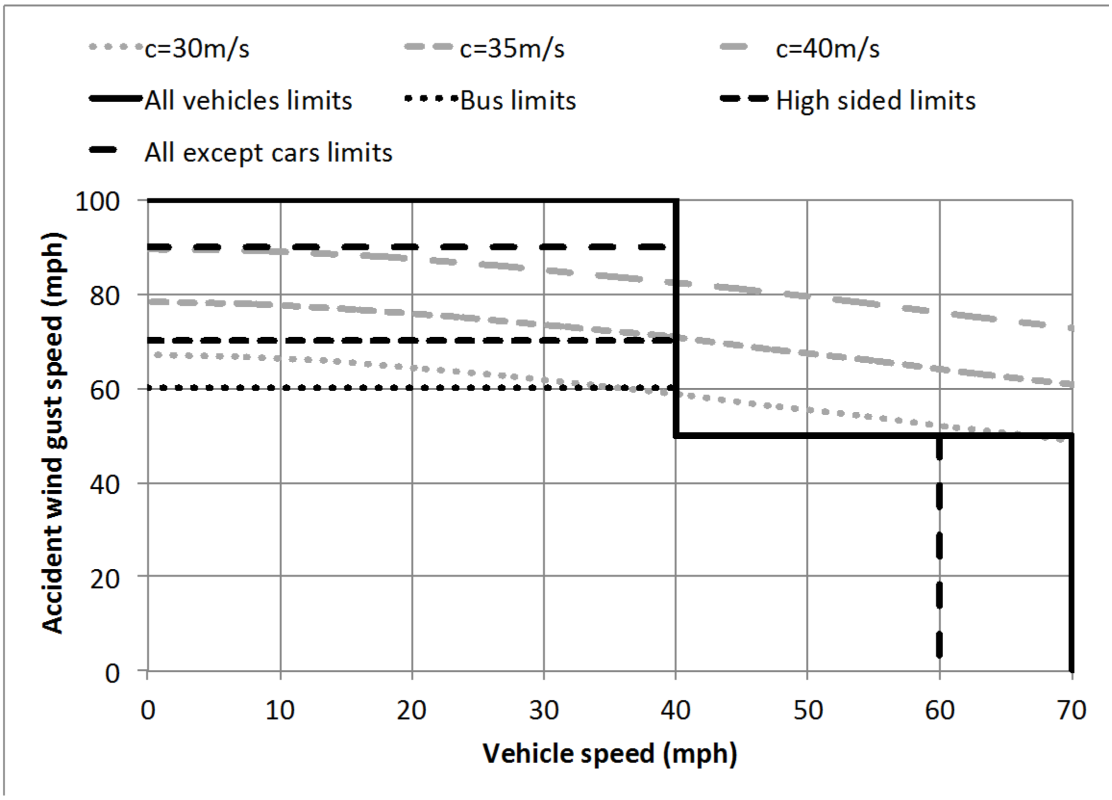


Figure 5. Minimum overturning wind speed for all wind directions against vehicle speed for values of *c* of 30, 35 and 40m/s and Queensferry Bridge limits for different vehicle categories

(vertical lines at 60 and 70mph indicate national speed limits for different vehicle classes)

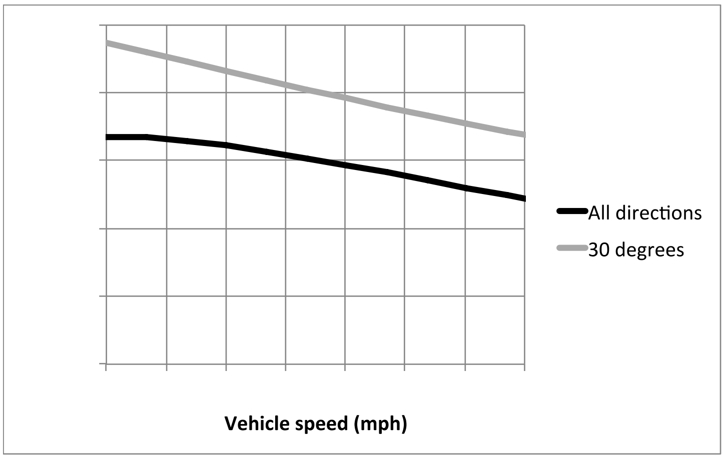


Figure 6. Overturning wind speeds against vehicle speed for all wind directions and 30 degree wind direction, for *c* = 30m/s

6. Use of the methodology

The above analysis gives a straightforward way of determining appropriate wind gust speed limits at exposed sites as follows.

- Determine the different vulnerable vehicle types that will use the road at that point in terms of size and weight, and calculate values of the characteristic velocity *c* for each.
- Determine either the lowest value of *c* for all traffic as the basis of vehicle restrictions, or divide the vehicles into easily identifiable categories for which it is practical to apply category specific restriction methods, with a value of *c* for each.
- If the directions of strong winds are very variable, then determine the accident wind speed / vehicle speed characteristic from equation (8) for each vehicle category.
- If there are identifiable periods when the wind will be predominantly along the roadway, determine wind speed / vehicle speed characteristic from equation (9) for each vehicle category for that case.
- Devise suitable, site-specific vehicle restrictions, such as those illustrated in figure 6 so that the operational conditions lie below the wind speed / vehicle speed characteristics at all times.

If the site is to be protected with wind fences, then this will result in a lower value of $C_{RL}(30)$ and thus a higher value of the characteristic velocity *c.* Equation (8) can then be used to determine vehicle restrictions with such protection in place, or alternatively can be used to give a target value of rolling moment coefficient that the protection should achieve.

The methodology can also potentially be used by vehicle manufacturers, who could use calculated values of *c* to give an indication of the crosswind stability of their vehicle designs. This could involve "tuning" of the value of the parameter α through modification of suspension parameters. Highway authorities could also easily incorporate the curves given by equation (8) into a route risk analysis, taking into account vehicle types and operational patterns and the gust wind speeds at sites along the route, which could be specified by the Weibull distribution format set out in Baker (2015).

7 Concluding remarks

This paper has presented a simple method that can be used in the specification of road vehicle restrictions at exposed sites during windy periods. It has deliberately taken a very simple, conservative approach in order to produce a methodology that is very straightforward to use in practice. The more complex static and dynamic methodologies developed by the author and by others still have a place however for particularly wind sensitive sites or for complex geometries – such as calculating vehicle behaviour as they move in and out of the shelter of bridge pylons. The following aspects of the simplified methodology are worthy of mention.

- A generalised formulation of an overturning wind characteristic that is valid for a wide range of vehicle types.
- The specification of individual vehicle vulnerability through the use of a characteristic velocity that can easily be calculated from weight and geometric parameters.
- A very simple formulation that relates dimensionless overturning wind speed to dimensionless vehicle velocity and can be used to specify vehicle restrictions at specific sites, or incorporated into route based risk calculations.

To enable the methodology to be used more widely the prime need is for data for the lee wheel rolling moment coefficient for a range of different vehicle types of relevance to different countries.

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