

The calculation of the overturning wind speed of large road vehicles at exposed sites

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1 **The calculation of the overturning wind speed of large**
2 **road vehicles at exposed sites**

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20 **Abstract**

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

37

38 **Notation**

39	A	Reference area (m ²)
40	c	Characteristic velocity (m/s) – equation 7
41	$C_{RL}(30)$	Lee wheel rolling moment coefficient at $\psi = 30$ degrees
42	$C_{RL}(\psi)$	Lee wheel rolling moment coefficient at ψ degrees
43	h	Reference height (m)
44	H	Vehicle height (m)
45	L	Vehicle length (m)
46	M	Vehicle mass (kg)
47	p	Wheel base semi-width (m)
48	R_L	Lee wheel rolling moment (Nm)
49	u	Wind gust velocity (m/s)
50	u_i	Wind gust velocity at which overturning occurs (m/s)
51	\bar{u}	u/c
52	\bar{u}_i	u_i/c
53	v	Vehicle velocity (m/s)
54	\bar{v}	v/c
55	V	Wind velocity relative to vehicle (equation 3) (m/s)
56	\bar{V}	V/c
57	α	Proportion of wheel unloading
58	β	Wind direction relative to vehicle direction of travel (°)
59	ψ	Yaw angle (equation 4)(°)
60	ρ	Density of air (kg/m ³)

61 **Keywords**

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

64 **1. Background**

65 High-sided road vehicles, particularly when unladen, are prone to overturning in high
66 winds, and there are frequent news reports of such accidents (eg BBC 2015, 2017a,
67 2017b). Safety considerations thus often make it necessary to place restrictions on the
68 movement of road traffic during wind storms, at sites such as long span bridges or on
69 exposed embankment sites. These restrictions can take the form of speed limits for
70 different types of vehicle, or for the complete closure of the road to vehicles of all types.
71 For example on the Queensferry Bridge in Scotland (which we will consider further later
72 in this paper), a blanket speed restriction of 40mph is put into place when the wind
73 gusts above 50mph (22.4m/s); double deck buses are not allowed to travel over the
74 bridge for gust speeds higher than 60mph (26.8m/s); high sided vehicles are banned
75 from crossing when wind gust speeds exceed 70mph (31.3m/s), all traffic except cars
76 are stopped for gusts above 90mph (40.3m/s) and the bridge is closed when gust speeds
77 reach 100mph (44.7m/s) (Forth Bridges, 2018). Similarly, restrictions on vehicle
78 movement can sometimes be required in urban areas, where the ground level wind
79 speeds around high-rise buildings can be sufficient to cause vehicle overturning
80 accidents (BBC, 2014).

81 There have been a number of investigations of the effects of cross winds on road
82 vehicles in the past. Clearly the most basic information that is required is a knowledge
83 of the cross wind forces and moments on vehicles. Wind tunnel measurements of these
84 forces for a variety of different vehicle types are reported in Baker (1988), Coleman and
85 Baker (1990), Sterling et al (2010), Cheli et al (2011a,b), Dorigati et al (2012), Han et al
86 (2014) and Liu et al (2016). Data is given for vehicles on flat ground, bridge,
87 embankment and viaduct scenarios. In addition Haan et al (2017) report measurements
88 on vehicle forces in a Tornado Vortex Generator and Xiang et al (2017) describe
89 measurements made using a moving model facility. More recently CFD calculations of
90 cross wind forces have been made - see Sterling et al (2010) and Stoyanoff et al (2015)

91 for example. As is the case in most sectors of wind engineering, full-scale data with
92 which to compare the wind tunnel and CFD measurements are understandably sparse
93 and the only investigations of this type known to the author are those of Sterling et al
94 (2010) for a stationary vehicle.

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

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

117 inputting the crosswind model into a driver simulator, thus introducing real human
118 involvement.

119 On many long span bridges and other exposed sites, wind barriers of different sorts are
120 used to protect traffic from high winds and to increase the wind gust speeds when traffic
121 restrictions are put into place. These barriers are usually designed using wind tunnel
122 tests and the level of shelter is usually quantified by a reduction in the forces and
123 moments on the vehicle, for example Chu et al (2013), Dorigati et al (2014), Chen et al
124 (2015) and Alonso-Estebanez et al (2017). These force and moment measurements are
125 not always related to the values of wind speed that may result in accidents and to the
126 risk of such accidents.

127 Ultimately the problem that arises when applying the results of the above research is
128 that the real life situation at any one site is complex, with a wide range of different
129 vehicle types, sizes, weights and levels of vulnerability, with wind approaching from a
130 range of directions and many of the methods outlined above (including those of the
131 author) are practically difficult and time consuming to use. Operationally any traffic
132 restrictions need to be quite simple and easy to implement, and must be aimed at
133 protecting the most vulnerable types of traffic at the site. Complex methodologies are
134 thus not always easy to use in practical situations, although they can be useful in
135 calibrating simpler methods. In addition it will be seen from what follows that there can
136 be considerable uncertainty in the aerodynamic forces and moments, with large
137 differences between the results of nominally similar wind tunnel tests or CFD
138 calculations. This paper thus in some ways steps back from recent developments in the
139 field and sets out a methodology for assessing safe wind speeds for vehicles in high
140 cross winds that, whilst as rigorous as possible, is deliberately simple and in a form that
141 can be used easily by bridge operators and transport authorities, both in the planning
142 and design stage for new infrastructure and operationally when considering whether
143 restrictions need to be applied. The methodology is outlined in section 2, and the

144 specification of aerodynamic force and moment coefficients considered in section 3. An
145 analysis that relates these coefficients to accident wind speeds is given in section 4, and
146 the application of this analysis set out in section 5. Section 6 considers how this
147 methodology can be used in wider contexts of risk assessment, and some concluding
148 remarks are made in section 7.

149 **2. Outline of methodology**

150 The methodology that is adopted is as follows.

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

- 174 • Both non-dimensionalised and dimensional curves of accident wind speed
- 175 against vehicle velocity can then be determined which can be used to specify
- 176 vehicle and wind speed restrictions at specific sites.
- 177
- 178

179 **3. Overturning moment coefficients**

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

182
$$C_{RL} = \frac{R_L}{0.5\rho AhV^2} \quad (1)$$

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

196
$$\frac{C_{RL}(\psi)}{C_{RL}(30)} = \frac{\sin(\psi)}{\sin(30)} \quad (2)$$

197 This is a slight modification of the method used by Baker (2013) for cross wind forces
198 on trains, where the reference yaw angle was taken as 40 degrees, and a rather more
199 complex curve fit used. Note that the values for most of the experiments diverge from
200 the simple curve for yaw angles of greater than 50 degrees, with the main exception
201 being the results of the full-scale experiments of Sterling et al (2010) – the filled grey
202 triangles. The author would argue that primacy should be given to such results, which
203 represent some sort of ground truth, and thus the simple curve of equation 2, which is a
204 reasonable representation of these results, is appropriate. Nonetheless this full-scale

205 data has much scatter that is not apparent from the results shown, but which again
 206 suggests a simple, conservative approach is appropriate.
 207

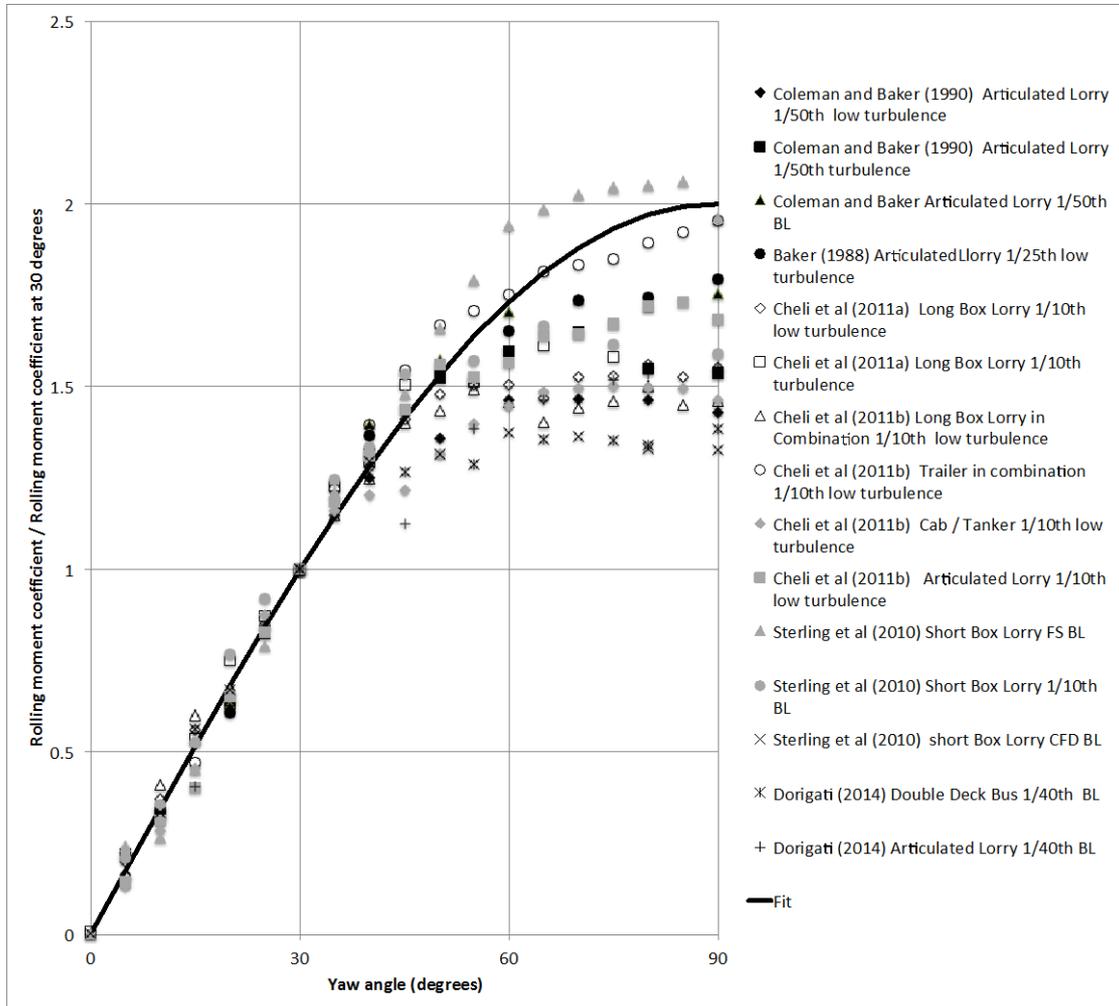


Figure 1 Collation of leeward wheel rolling moment characteristic data

(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 $A=10\text{m}^2$ and $h = 3\text{m}$	$C_{RL}(30)$ 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)

208 The values of the rolling moment coefficients at a yaw angle of 30 degrees are given in
209 table 1. Two values of the coefficient are give, the first based on values of A and h of
210 10m^2 and 3m respectively (which are conventional, nominal values) and the second
211 based on values of A given by the product of the overall vehicle length L and overall
212 vehicle height H , and values of h given directly by H . The first values show a steady
213 increase of the coefficient with the length of the vehicle as would be expected, for all the
214 sharp edged vehicles, but with the Cab / Tanker value (without sharp edges in the cross
215 section) having a lower value than would be expected for its length. Again, with
216 exception of the Cab / Tanker, the second set of values are almost all within the range of
217 0.3 to 0.5, with the values for the Short Box Lorry being in the range 0.31 to 0.38; for the

218 Long Box Lorry in the range 0.36 to 0.39 and for the Articulated Lorry being between
219 0.41 and 0.52, with the exception of the results of Cheli (2011b) which lie significantly
220 below this range. These ranges indicate the level of uncertainty that attached to any
221 estimation of rolling moment coefficients obtained experimentally or computationally.

222

223

224 **4. Accident wind speed calculation**

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

$$228 \quad V^2 = ((u\cos(\beta) + v)^2 + (u\sin(\beta))^2) \quad (3)$$

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

$$230 \quad \tan(\psi) = \frac{u \sin(\beta)}{u \cos(\beta) + v} \quad (4)$$

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

$$233 \quad C_{RL}(0.5\rho AhV^2) = Mgp \quad (5)$$

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

$$237 \quad C_{RL}(0.5\rho AhV^2) = \alpha Mgp$$

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

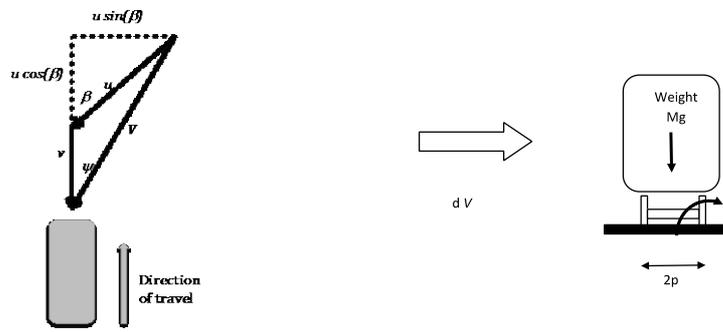
$$241 \quad (\bar{v}^2 + \bar{u}_i^2 + 2\bar{u}_i\bar{v}\cos(\beta))(\bar{u}_i\sin(\beta))^2 = 1 \quad (6)$$

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

$$244 \quad c = \sqrt{\frac{\alpha Mgp}{\rho C_{RL}(30)Ah}} \quad (7)$$

245 This expression in equation (6) gives the relationship between the dimensionless
 246 crosswind speed for an overturning incident to occur, the wind direction and the
 247 dimensionless vehicle speed, with the vehicle parameters being fully specified by the
 248 characteristic velocity. It is completely general and can be applied to all vehicles and
 249 situations where the assumptions set out in section 2 apply. It is also very simple in

250 form, although can only be solved analytically for very specific cases. This will be seen to
 251 be its major utility.



(a) Velocity vectors

(b) Static model

Figure 2 Velocities and rolling moments

252

253

254 **5. Application of methodology**

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

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

273
$$\bar{u}_i = e^{-\left(\frac{\bar{v}}{2.4}\right)^{1.41}} \quad (8)$$

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

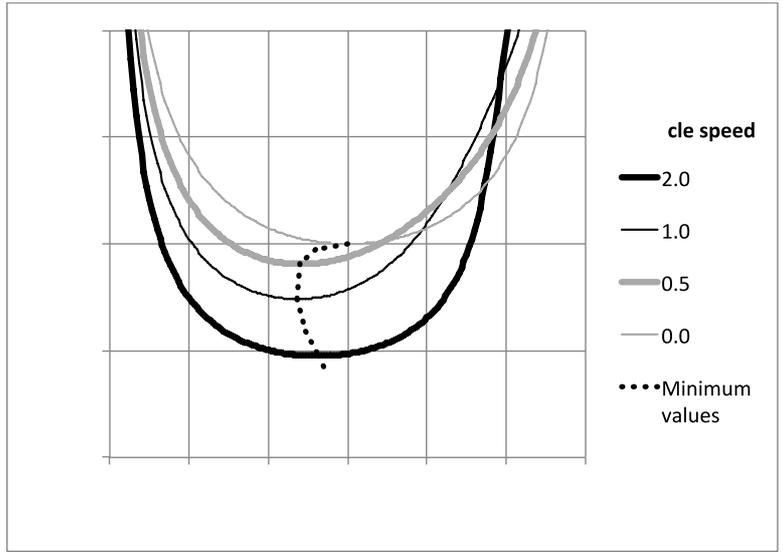
275
$$\bar{u}_i = 1.41e^{-\left(\frac{\bar{v}}{3}\right)^{1.05}} \quad (9)$$

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

278 The above analysis has been expressed in dimensionless terms, and as such can give
279 generalised formulae applicable to a range of situations. In practical terms however it is

280 useful to express the results in dimensional terms. To do this values of the characteristic
281 velocity c are required. Typical values of this parameter are given in table 2 for a small
282 number of vehicle categories where aerodynamic information is available.
283 Representative values of the weights and dimensions are assumed. It can be seen that
284 for unladen vehicles the values are between 30m/s and 40m/s, with the laden values
285 being very much higher. Figure 5 thus shows the variation of the minimum value of the
286 overturning wind speed for all wind directions against vehicle speed for values of c of
287 30, 35 and 40m/s. In both cases the units used for speed are miles per hour, which is of
288 course scientifically non-standard, but are the units actually used in practice in the UK
289 and USA. Also shown are the vehicle restriction limits for Queensferry Bridge in
290 Scotland outlined in section 1, although only those for double deck buses and high-sided
291 vehicles are relevant to the current methodology (section 1). These limits ensure that
292 the $c = 30\text{m/s}$ line and $c = 35\text{m/s}$ lines are not crossed by buses and high sided vehicles
293 respectively, which seems very sensible in the light of the values of c given in table 2.
294 The analysis and the operational experience of this particular bridge are thus in
295 reasonable agreement.
296 Finally figure 6 shows the wind speeds for vehicle overturning for the minimum values
297 and the minimum values for wind directions of less than 30 degrees to the vehicle
298 direction of travel. The latter can be seen to be significantly higher than the former,
299 showing the potential for relaxing wind and vehicle speed limits if the wind direction is
300 known to be predominantly along the roadway.

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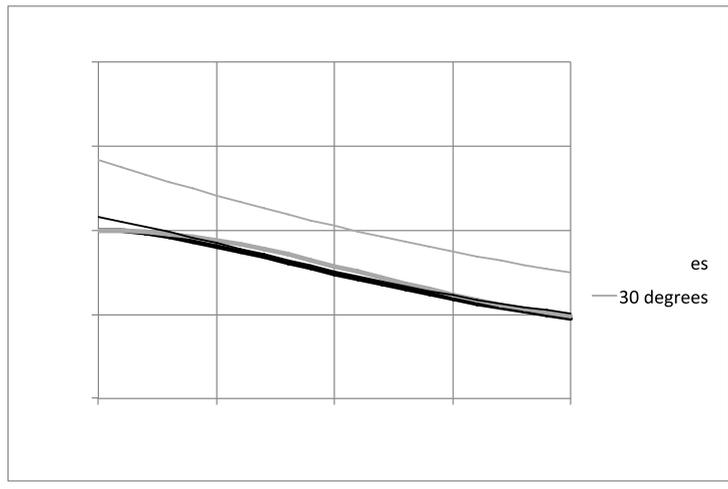
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Figure 3. Non-dimensional accident wind speeds against wind direction for a

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range of non-dimensional vehicle velocities

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Figure 4. Values of non-dimensional accident wind speeds against non-

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dimensional vehicle velocities for the minimum values and different wind

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direction values.

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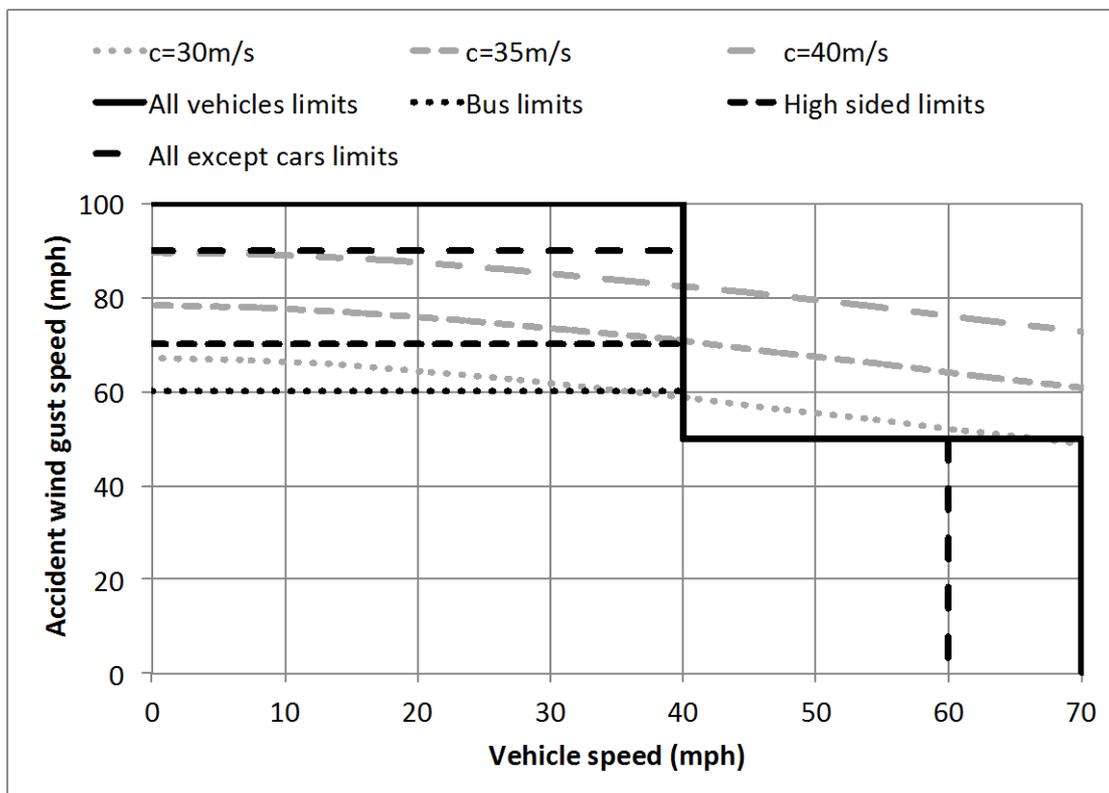
	Unladen mass M (kg)	Laden mass M (kg)	L (m)	H (m)	p (m)	$C_{RL}(30)$	Unladen c (m/s)	Laden c (m/s)
Small Box lorry	7000	16000	8.0	3.5	1.2	0.4	40.2	60.8
Large Box Lorry	9000	18000	12.0	3.5	1.2	0.4	37.2	52.7
Articulated lorry	16000	40000	15.0	4.0	1.2	0.5	34.3	54.2
Double Deck Bus	10000	14000	12.0	4.4	1.2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

313

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Table 2 Calculation of characteristic velocities

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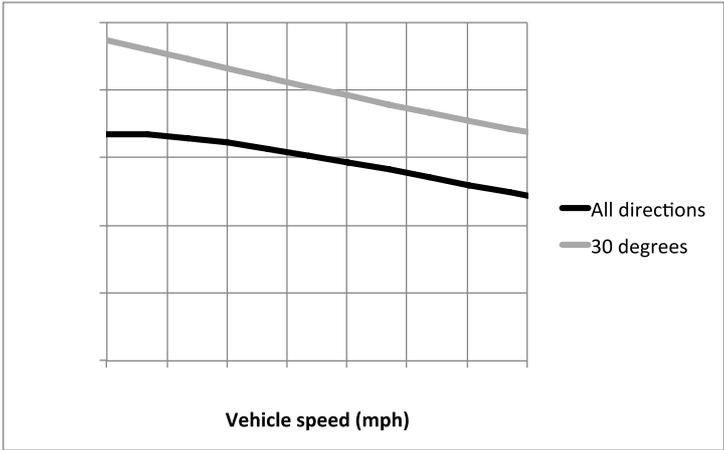


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Figure 5. Minimum overturning wind speed for all wind directions against vehicle speed for values of c of 30, 35 and 40m/s and Queensferry Bridge limits for different vehicle categories

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

322



323

324

325 **Figure 6. Overturning wind speeds against vehicle speed for all wind directions**

326

and 30 degree wind direction, for $c = 30\text{m/s}$

327

328

329

330 **6. Use of the methodology**

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

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

349 If the site is to be protected with wind fences, then this will result in a lower value of
350 $C_{RL}(30)$ and thus a higher value of the characteristic velocity c . Equation (8) can then be
351 used to determine vehicle restrictions with such protection in place, or alternatively can
352 be used to give a target value of rolling moment coefficient that the protection should
353 achieve.

354 The methodology can also potentially be used by vehicle manufacturers, who could use
355 calculated values of c to give an indication of the crosswind stability of their vehicle
356 designs. This could involve “tuning” of the value of the parameter α through

357 modification of suspension parameters. Highway authorities could also easily
358 incorporate the curves given by equation (8) into a route risk analysis, taking into
359 account vehicle types and operational patterns and the gust wind speeds at sites along
360 the route, which could be specified by the Weibull distribution format set out in Baker
361 (2015).

362

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364

365 **7 Concluding remarks**

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

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

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

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386 **References**

- 387 A. Alonso-Estebanez, J.J. Del Coz Díaz, F.P. Alvarez Rabanal, P. Pascual-Munoz, 2017,
388 "Performance analysis of wind fence models when used for truck protection under
389 crosswind through numerical modelling", Journal of Wind Engineering and Industrial
390 Aerodynamics 168, 20-31, <http://dx.doi.org/10.1016/j.jweia.2017.04.021>
- 391 T. Argentini, E. Ozkan, D. Rocchi, L. Rosa, A. Zasso, 2011, "Cross-wind effects on a vehicle
392 crossing the wake of a bridge pylon", Journal of Wind Engineering and Industrial
393 Aerodynamics 99, 734-740, <http://dx.doi.org/10.1016/j.jweia.2011.01.021>
- 394 C.J. Baker, 1986, "A simplified analysis of various types of wind induced road vehicle
395 accidents", Journal of Wind Engineering and Industrial Aerodynamics, 22, 1, 69-85,
396 [http://dx.doi.org/10.1016/0167-6105\(86\)90012-7](http://dx.doi.org/10.1016/0167-6105(86)90012-7)
- 397 C.J. Baker, 1987, "Measures to control vehicle movement at exposed sites during windy
398 periods", Journal of Wind Engineering and Industrial Aerodynamics, 25, 151-167,
399 [http://dx.doi.org/10.1016/0167-6105\(87\)90013-4](http://dx.doi.org/10.1016/0167-6105(87)90013-4)
- 400 C.J. Baker, 1988, "High sided articulated lorries in strong cross winds", Journal of Wind
401 Engineering and Industrial Aerodynamics, 31, 67-85, [http://dx.doi.org/10.1016/0167-](http://dx.doi.org/10.1016/0167-6105(88)90188-2)
402 [6105\(88\)90188-2](http://dx.doi.org/10.1016/0167-6105(88)90188-2)
- 403 C.J. Baker, 1991, "Ground vehicles in high cross winds - Part 3 The interaction of
404 aerodynamic forces and the vehicle system", Journal of Fluids and Structures 5, 221-241,
405 [http://dx.doi.org/10.1016/0889-9746\(91\)90478-8](http://dx.doi.org/10.1016/0889-9746(91)90478-8)
- 406 C J Baker, 2013, "A framework for the consideration of the effects of crosswinds on
407 trains", Journal of Wind Engineering and Industrial Aerodynamics 123, 130-142,
408 <http://dx.doi.org/10.1016/j.jweia.2013.09.01>
- 409 C J Baker, 2015, "Risk analysis of pedestrian and vehicle safety in windy environments",
410 Journal of Wind Engineering and Industrial Aerodynamics, 147, 283-290,
411 <http://dx.doi.org/10.1016/j.jweia.2015.10.001>

412 C.J. Baker, S. Reynolds, 1991, "Wind induced accidents of road vehicles" Accident Analysis
413 and Prevention 24, 6, 559-575, [http://dx.doi.org/10.1016/0001-4575\(92\)90009-8](http://dx.doi.org/10.1016/0001-4575(92)90009-8)

414 M. Batista, M. Perkovič, 2014 "A simple static analysis of moving road vehicle under
415 crosswind", Journal of Wind Engineering and Industrial Aerodynamics 128, 105-113,
416 <http://dx.doi.org/10.1016/j.jweia.2014.02.009>

417 BBC, 2014, "Bridgewater Place wind reduction plans unveiled",
418 <https://www.bbc.co.uk/news/uk-england-leeds-25760733>

419 BBC, 2015, "Humber Bridge winds blow over lorry", [https://www.bbc.co.uk/news/uk-](https://www.bbc.co.uk/news/uk-england-humber-32137694)
420 [england-humber-32137694](https://www.bbc.co.uk/news/uk-england-humber-32137694)

421 BBC, 2017a, "Strong winds in US topple truck on highway",
422 [https://www.bbc.co.uk/news/av/world-us-canada-38940832/strong-winds-in-us-topple-truck-](https://www.bbc.co.uk/news/av/world-us-canada-38940832/strong-winds-in-us-topple-truck-on-highway)
423 [on-highway](https://www.bbc.co.uk/news/av/world-us-canada-38940832/strong-winds-in-us-topple-truck-on-highway)

424 BBC, 2017b, "Forth Road Bridge reopens after lorry blown over",
425 <https://www.bbc.co.uk/news/uk-scotland-38575843>

426 F. Cheli, P. Belforte, S. Melzi, E. Sabbioni, G. Tomasini, 2006, "Numerical-experimental
427 approach for evaluating cross-wind aerodynamic effects on heavy vehicles", Vehicle
428 System Dynamics, 44, 1, 791 – 804 <http://dx.doi.org/10.1080/00423110600886689>

429 F. Cheli, R. Corradi, E. Sabbioni, G. Tomasini, 2011 a, "Wind tunnel tests on heavy road
430 vehicles: Cross wind induced loads—Part 1", Journal of Wind Engineering and Industrial
431 Aerodynamics 99, 1000-1010 <http://dx.doi.10.1016/j.jweia.2011.07.009>

432 F. Cheli, F. Ripamonti, E. Sabbioni, G. Tomasini 2011b "Wind tunnel tests on heavy road
433 vehicles: Cross wind induced loads—Part 1", Journal of Wind Engineering and Industrial
434 Aerodynamics 99, 1011-1024 <http://dx.doi.10.1016/j.jweia.2011.07.007>

435 N. Chen, Y. Lin, B. Wang, Y. Su, H. Xiang, 2015, "Effects of wind barrier on the safety of
436 vehicles driven on bridges", Journal of Wind Engineering and Industrial Aerodynamics
437 143, 113-127, <http://dx.doi.org/10.1016/j.jweia.2015.04.021>

438 C-R. Chu, C-Y. Chang, C-J Huang, T-R. Wu, C-Y. Wang, M-Y. Liu, 2013, "Windbreak
439 protection for road vehicles against crosswind", Journal of Wind Engineering and
440 Industrial Aerodynamics 143, 113-127, <http://dx.doi.org/10.1016/j.jweia.2013.02.001>
441 S.A. Coleman, C.J. Baker, 1990, "High sided road vehicles in cross winds", Journal of Wind
442 Engineering and Industrial Aerodynamics 36, 1383-1397,
443 [http://dx.doi.org/10.1016/0167-6105\(90\)90134-X](http://dx.doi.org/10.1016/0167-6105(90)90134-X)
444 F. Dorigatti, M. Sterling, D. Rocchi, M. Belloli, A.D. Quinn, C.J. Baker, E. Ozkan, 2012,
445 "Wind tunnel measurements of crosswind loads on high sided vehicles over long span
446 bridges", Journal of Wind Engineering and Industrial Aerodynamics 107-108, 214-224,
447 <http://dx.doi.org/10.1016/j.jweia.2012.04.017>
448 Forth Bridges (2018) "Wind and weather" [https://www.theforthbridges.org/plan-your-](https://www.theforthbridges.org/plan-your-journey/wind-and-weather/)
449 [journey/wind-and-weather/](https://www.theforthbridges.org/plan-your-journey/wind-and-weather/)
450 F.L. Haan, P.P. Sarkar, G. A. Kopp, D. A. Stedman, 2017 "Critical wind speeds for tornado-
451 induced vehicle movements", Journal of Wind Engineering and Industrial Aerodynamics
452 168, 1-8, <http://dx.doi.org/10.1016/j.jweia.2017.04.014>
453 Y. Han, C.S. Cai, J. Zhang, S. Chen, X. He, 2014 "Effects of aerodynamic parameters on the
454 dynamic responses of road vehicles and bridges under cross winds", Journal of Wind
455 Engineering and Industrial Aerodynamics 134, 78-95,
456 <http://dx.doi.org/10.1016/j.jweia.2014.08.013>
457 S-J. Kim, C-H Yoo, H-K. Kim, 2016, "Vulnerability assessment for the hazards of
458 crosswinds when vehicles cross a bridge deck", Journal of Wind Engineering and
459 Industrial Aerodynamics 156, 62-71, <http://dx.doi.org/10.1016/j.jweia.2016.07.005>
460 X. Liu, Y Han, C.S. Cai, M, Levitan, D. Nikitopoulos, 2016 "Wind tunnel tests for mean
461 wind loads on road vehicles", Journal of Wind Engineering and Industrial Aerodynamics
462 150, 15-21, <http://dx.doi.org/10.1016/j.jweia.2015.12.004>

463 Y. Maruyama , F Yamazaki, 2006, “Driving simulator experiment on the moving stability
464 of an automobile under strong crosswind”, Journal of Wind Engineering and Industrial
465 Aerodynamics 94, 191-205, <http://dx.doi.org/10.1016/j.jweia.2005.12.006>
466 D. Rocchi, L. Rosa, E. Sabbioni n, M. Sbroisi, M. Belloli, 2012, A” numerical–experimental
467 methodology for simulating the aerodynamic forces acting on a moving vehicle passing
468 through the wake of a bridge tower under cross wind”, Journal of Wind Engineering and
469 Industrial Aerodynamics 104-106, 256-265,
470 <http://dx.doi.org/10.1016/j.jweia.2012.03.012>
471 J. Snæbjornsson, , C.J. Baker, R. Sigbjornsson, 2007 “Probabilistic assessment of road
472 vehicle safety in windy environments”, Journal of Wind Engineering and Industrial
473 Aerodynamics 95, 1445-1462, <http://dx.doi.org/10.1016/j.jweia.2007.02.020>
474 M. Sterling, A. Quinn, D. Hargreaves, F. Cheli, F. Sabbioni, G. Tomasini, D. Delaunay, C.J.
475 Baker, and H. Moran, 2010, “A comparison of different methods to evaluate the wind
476 induced forces on a high sided lorry”, Journal of Wind Engineering & Industrial
477 Aerodynamics 98 10–20, <http://dx.doi.org/10.1016/j.jweia.209.08.008>
478 S. Stoyanoffa, P. Dallairea, T. Zolib, G. Daly, 2015, “Vehicle roll-over stability in strong
479 winds on long-span bridges”, Bridge Structures 149–162
480 <http://dx.doi.org/10.3233/BRS-160094>
481 B. Wang, Y. Xu, 2015, “Safety analysis of a road vehicle passing by a bridge tower under
482 crosswinds”, Journal of Wind Engineering and Industrial Aerodynamics 137, 25-36,
483 <http://dx.doi.org/10.1016/j.jweia.2014.11.017>
484 H. Xiang, Y. Li, S. Chen, C. Li, 2017, “A wind tunnel test method on aerodynamic
485 characteristics of moving vehicles under crosswinds”, Journal of Wind Engineering and
486 Industrial Aerodynamics , 163,15-23, <http://dx.doi.org/10.1016/j.jweia.2017.01.013>
487 Y, Zhou, S, Chen, 2015, “Fully coupled driving safety analysis of moving traffic on long-
488 span bridges subjected to crosswind”, Journal of Wind Engineering and Industrial
489 Aerodynamics , 143, 1-18, <http://dx.doi.org/10.1016/j.jweia.2015.04.015>

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