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GM/RC2542 Recommendations for Determination of Aerodynamic Rolling Moment Coefficient Issue One: August 2009 Railway Group Recommendations for GM/RT2142



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Recommendations for Determination of Aerodynamic Rolling Moment Coefficient

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Supply

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Recommendations for Determination of Aerodynamic Rolling Moment Coefficient

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Part 1 Introduction

1.1 Purpose and structure of this document

This document gives details of a recommended method which, if followed, would meet the requirements of Railway Group Standard GM/RT2142.

Should an infrastructure manager or a railway undertaking choose not to follow the recommended method of meeting the requirements of GM/RT2142 laid out in this document, it should assure itself that the method it is following is as effective, and no less safe, than the method that is recommended here.

Relevant requirements in GM/RT2142 are reproduced in the sections that follow. Recommendations are provided as a series of sequentially numbered clauses prefixed 'RC'.

Specific responsibilities and compliance requirements are laid down in the Railway Group Standard itself.

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1.3 Approval and authorisation of this document

The content of this document was approved by:

Rolling Stock Standards Committee on 01 May 2009.

This document was authorised by RSSB on 19 June 2009.

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Part 2 Recommendations for Determination of Aerodynamic Rolling Moment Coefficient

2.1 Introduction

2.1.1 Process to demonstrate compliance with GM/RT2142

- 2.1.1.1 This code of practice provides details of methodologies for determining a more accurate aerodynamic rolling moment coefficient for the vehicle, as an alternative to using the benchmark aerodynamic rolling moment coefficient equations in GM/RT2142.
- 2.1.1.2 GM/RT2142 permits several approaches to achieving satisfactory 'resistance of railway vehicles to roll-over in gales'. The appropriate approach depends mainly on the maximum speed of the vehicle, whether it will operate at conventional cant deficiencies and obviously on the shape, suspension design and overall mass of the vehicle. A description of the approaches to compliance is outlined below and demonstrated visually by the flow chart in Figure 1 of this code of practice.
- 2.1.1.3 The first decision point concerns the vehicle's maximum operational speed. Where the vehicles maximum operational speed is intended to be above 140 mile/h (63 m/s), a separate acceptance strategy needs to be developed with the support of a specialist in the field of rail vehicle aerodynamics as it is outside the scope of this document and GM/RT2142.
- 2.1.1.4 The next decision point concerns whether or not the vehicle will be operating at conventional cant deficiencies (up to 6° for passenger carrying vehicles and up to 4.25° for freight vehicles). If it is intended to operate at greater than the conventional cant deficiencies, specialist technical expertise should be used to determine the vehicle aerodynamic rolling moment coefficient about the lee rail in accordance with the requirements of 2.2.1.1 d) of GM/RT2142. The specialist in the field of rail vehicle aerodynamics can recommend what level of wind tunnel testing is required. This code of practice describes two levels of wind tunnel testing for vehicles operating at higher than conventional cant deficiencies:
- a) For vehicles predicted to have a very low intrinsic roll-over wind speed (when calculated using the benchmark aerodynamic rolling moment coefficient equations in GM/RT2142), the more detailed and accurate of the two wind tunnel testing methodologies is likely to be adopted. This is an 'atmospheric boundary layer with turbulence' test and is described in RC016 to RC085 of this document. The more accurate test method would produce the least conservative results and would be most likely to lead to the vehicle's intrinsic roll-over wind speed exceeding the minimum acceptable intrinsic roll-over wind speed.
 - b) For vehicles that narrowly fail to exceed the minimum acceptable intrinsic roll-over wind speed (when calculated using the aerodynamic rolling moment coefficient equations in GM/RT2142), a less complicated, but more economical wind tunnel testing methodology is likely to be recommended. This is a 'uniform profile, low turbulence' test and is described in Appendix B of this code of practice. The results from this test would be more conservative than those produced from the atmospheric boundary layer test method and would lead to a lower value of intrinsic roll-over wind speed.

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- 2.1.1.5 For vehicles operating within conventional cant deficiencies, no wind tunnel testing is required if the requirements in GM/RT2142 are satisfied (that is the calculated intrinsic roll-over wind speed is greater than the minimum required). If, however, the minimum acceptable intrinsic roll-over wind speed is not achieved, it is recommended that specialist technical expertise be sought to provide guidance. Options include: refining the calculated minimum intrinsic roll-over wind speed, applying for a deviation or carrying out wind tunnel tests. Where wind tunnel tests are the recommended way forward then a 'uniform profile, low turbulence' test should be used. The methodology is described in Appendix A of this document. This test should result in less conservative results than those obtained using the benchmark aerodynamic rolling moment coefficient equations in GM/RT2142 and should enable the minimum acceptable intrinsic roll-over wind speed to be exceeded in most cases.
- 2.1.1.6 Finally, if the candidate vehicle still fails to meet the minimum intrinsic roll-over wind speed (after using the measured aerodynamic rolling moment coefficient determined from wind tunnel tests) then an application for a deviation can be applied for. This approach is likely to require involvement of specialist technical expertise in the field of rail vehicle aerodynamics and be based around a risk assessment. Operational limitations such as reduced maximum speed or increased vehicle mass (tare) may have to be applied. If the deviation is rejected then the vehicle will need to be redesigned.

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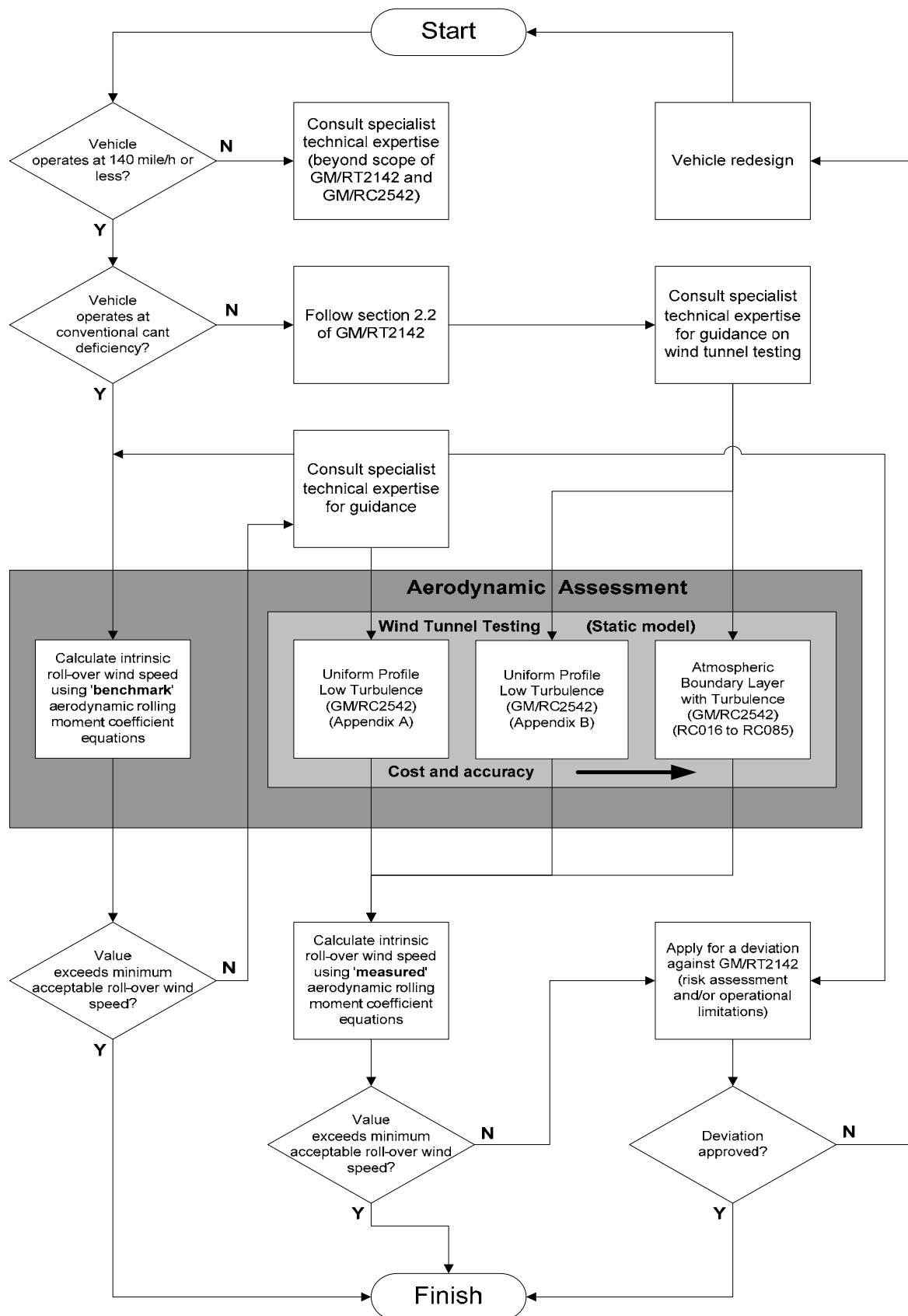


Figure 1 Flow chart showing routes to compliance with GM/RT2142

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2.1.2 Scope of the code of practice

- RC001 This code of practice provides recommendations for only one clause in GM/RT2142. GM/RT2142 mandates the determination of a number of elements of vehicle characteristics that are used to establish the maximum permissible speed of a train along a route, such that the train will not overturn in high winds. The data is utilised by the infrastructure manager in accordance with GC/RT5021 and GC/RC5521.

GM/RT2142 Resistance of Railway Vehicles to Roll-Over in Gales

2.2 Vehicle characteristics to be supplied to the infrastructure manager (for vehicles operating above conventional cant deficiencies)

2.2.1 Vehicle characteristics required for determining maximum enhanced permissible speeds

- 2.2.1.1 In addition to the requirements set out in 2.1.1.1, railway undertakings shall determine the following vehicle characteristics for a vehicle designed to carry people that operates at cant deficiencies greater than 6° or a freight vehicle that operates at cant deficiencies greater than 4.25°:
- Maximum design operating speed.
 - Total projected side area of vehicle or side area used to determine its aerodynamic rolling moment coefficient about the lee rail from tests.
 - Vehicle mean longitudinal roof height above axle centreline or height used to determine its aerodynamic rolling moment coefficient about the lee rail from tests.
 - Vehicle aerodynamic rolling moment coefficient about the lee rail over the range of yaw angles from 15° to 90°, taking account of the position of the vehicle in the train. Two sets of data are required (except for freight vehicles), one for the leading vehicle and one for a trailing vehicle in the train.
 - Vehicle tare mass.
 - Height of vehicle centre of gravity above rail level and the effects the suspension characteristics may have on the vehicle centre of gravity including changes due to the tilting of the vehicle.

- RC002 With regard to the requirements in GM/RT2142, the train speed, vehicle mass and height of the centre of mass that should be used in the calculation are determined from the train operational and construction characteristics.

- RC003 This code of practice is primarily concerned with the determination of the vehicle aerodynamic rolling moment coefficient required by 2.2.1.1 d) of GM/RT2142 although in association with this parameter it is also necessary to define the requirements of c) the vehicle mean longitudinal roof height (H), and b) the total projected side area (A). In particular, this code of practice specifies the type of wind tunnel test that should be used to determine the vehicle's aerodynamic rolling moment coefficient and sets out a method by which the results that are obtained can be benchmarked against a standard set of measurements.

2.1.3 The purpose of the wind tunnel tests

- RC004 2.2.1.1 of GM/RT2142 requires the determination of the aerodynamic rolling moment coefficient for passenger carrying or freight vehicles operating at greater than conventional cant deficiencies. The main part of this code of practice is directed toward this requirement. For vehicles operating at conventional cant deficiencies A.5.1 and B.3.3 of

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GM/RT2142, also permits more accurate values of the aerodynamic rolling moment coefficient relevant to actual vehicles to be obtained from suitable wind tunnel tests. These values can be used as an alternative to the benchmark equations supplied in Table A.1 and Table A.2 of GM/RT2142. Table 1 of this code of practice outlines the different requirements of GM/RT2142 and the type of tests required.

Requirement in GM/RT2142	Type of wind tunnel test	Comment
Conventional cant deficiency A.5.1 and B.3.3	Uniform profile, low turbulence	The aerodynamic rolling moment coefficient determined by this test is more accurate and less conservative than using the benchmark equations for streamlined, unstreamlined or intermediate vehicles. <i>Relatively low cost test.</i>
Greater than conventional cant deficiency 1.2.1.3 and 2.2.1.1 d)	Atmospheric boundary layer with turbulence	Most accurate aerodynamic rolling moment coefficient determination. Least conservative, state-of-the-art, but most complex, method. <i>Relatively high cost test.</i>
Greater than conventional cant deficiency 1.2.1.3 and 2.2.1.1 d)	Uniform profile, low turbulence	A less accurate determination of aerodynamic rolling moment coefficient. More conservative than the atmospheric boundary layer method, but less complex. <i>Relatively low cost test.</i>

Table 1 Types of wind tunnel tests for compliance with GM/RT2142

- RC005** The purpose of the wind tunnel tests is to enable the determination of the aerodynamic rolling moment coefficient about the lee rail for a range of route characteristics over which the vehicle will operate, including both level ground and embankments. This coefficient is a non-dimensional form of the full-scale wind-induced moment acting around the line of contact between wheels and the lee rail. It is this moment that unloads upwind wheels in strong winds and, at the limit, could cause a vehicle to roll over. GM/RT2142 requires the value of this coefficient at yaw angles (the angle between the vehicle axis and the wind tunnel flow direction) between 15° and 90°. The step interval used (for example 5°, 10° or 15°) is not critical but should not be larger than 15°. Step intervals of 15° have been used for the benchmark vehicles and examples provided in this code of practice.
- RC006** The wind tunnel coefficients are used to calculate the effects of strong winds on vehicle stability. This code of practice does not address this stability analysis. The stability analysis requires the peak aerodynamic rolling moment coefficient, $\hat{C}_R$, which is proportional to the ratio of the peak aerodynamic rolling moment to the peak dynamic pressure. This differs from the mean aerodynamic rolling moment coefficient, $\overline{C}_R$, which is proportional to the ratio of the mean aerodynamic rolling moment to the mean dynamic pressure. The peak aerodynamic rolling moment coefficient is generally lower than the mean aerodynamic rolling moment coefficient. This is because the high frequency fluctuations in dynamic pressure are due to gusts with an eddy dimension less than the vehicle length, and these do not produce corresponding high frequency force peaks because of lack of spatial correlation over the surface of the vehicle. In addition, the ratio of the peak to the mean aerodynamic rolling moment coefficient values varies with the reference height used because of the nature of the velocity and turbulence variation with height above the ground. Taken together, these effects can result in ratios of peak to mean aerodynamic rolling moment coefficients as low as 0.5.

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2.1.4 The nature of the wind tunnel tests

- RC007 The type of wind tunnel test that is recommended here is one using static models of the train in a large environmental wind tunnel in which the atmospheric turbulence and shear has been simulated accurately. This approach can be expected to be valid for the range of train operating speeds generally found in Great Britain (up to 140 mile/h (225 km/h)). However, if wind tunnel tests are being carried out for higher train speeds (above 140 mile/h (225 km/h)) then this turbulence simulation is unlikely to be adequately representative, particularly at low yaw angles and further specialist technical expertise in rail vehicle aerodynamics should be sought.
- RC008 The type of wind tunnel test that is specified, using static train models in an atmospheric boundary layer simulation, is effectively a compromise between simple static model tests with no representation of the atmospheric wind, and more complex tests that use moving models to simulate the movement of the train over the ground with an atmospheric boundary layer.
- RC009 Low turbulence tests (tests without an atmospheric boundary layer simulation and having instead a uniform, low turbulence flow) are sometimes used to obtain an approximate measurement of the mean aerodynamic rolling moment coefficient about the lee rail $\bar{C}_R$. Use of this mean aerodynamic rolling moment coefficient together with a gust wind speed is likely to give a conservative (high) estimate of the peak rolling moment that could be expected due to the gust wind speed. These simpler tests are therefore potentially useful for giving a relatively low cost indication of the magnitude of the aerodynamic rolling moment for applications where the train is expected to be more stable than other trains operating on the route (for example if it is heavier, or operates at lower speeds). If this approach is adopted, it should be on the basis of expert advice confirming that the approach would be conservative and appropriate for the particular case. There would also be specific experimental requirements. These are outlined in Appendix B. Such tests may also be used to determine the aerodynamic rolling moment coefficients for vehicles operating at standard cant deficiencies. These have specific experimental requirements as outlined in Appendix A.
- RC010 Although a particular form of wind tunnel test has been adopted in this code of practice, by no means have all modelling issues associated with such tests been fully resolved. For example, the measurement of aerodynamic rolling moment coefficient about the lee rail for vehicles on an embankment is still a significant issue requiring further research. In principle, tests with a moving model are required to ensure the correct relative velocities between train and ground and train and wind. The method proposed here can only be regarded as a simplification of these requirements. Nonetheless it is likely that, as the main effect of vehicle motion on the forces and moments will be on lift force, which is usually a relatively small component of the aerodynamic rolling moment coefficient about the lee rail, any errors will be marginal. It should be noted that, at the time of writing, the use of computational fluid dynamics to predict the aerodynamic rolling moment coefficient about the lee rail in an absolute sense is not recommended due to, for example, difficulties in grid generation and choice of turbulence model. However, such calculations could be useful in a comparative sense to investigate the variations of coefficients between different, but similar, types of train.
- RC011 As stated in RC006, it is the peak aerodynamic rolling moment coefficient about the lee rail $\hat{C}_R$ which is required for stability analysis, and this differs from the mean aerodynamic rolling moment coefficient $\bar{C}_R$. $\hat{C}_R$ is determined directly for yaw angles of 90° but is determined indirectly from $\bar{C}_R$ at lower yaw angles. This indirect procedure is used to remove the biasing effect of taking peak coefficients derived on a stationary train (where load maxima arise because of fluctuations in both wind speed and direction) as estimates for loads on a moving train (where the dominant cause of load maxima is the fluctuations in

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relative wind speed). For this reason, both types of coefficient are required as set out in this code of practice.

2.1.5 The benchmarking approach

RC012 Recent research work associated with the West Coast Route Modernisation project and earlier analyses has shown that different wind tunnels can give significantly different estimates for the aerodynamic rolling moment coefficient about the lee rail. This is due to the differences in wind tunnel techniques due to different flow profiles and turbulence modelling in different wind tunnels. The limits and tolerances given by this code of practice limit the range of variation but, will not eliminate it altogether. A benchmarking approach has therefore been adopted. This requires that whenever a new vehicle is tested, a model of a benchmark vehicle (for which reliable experimental results are already available) should also be tested. Appendix D defines the benchmark case, from tests of the Class 390, to be used for new leading vehicles. Appendix E defines the benchmark case, for the Mark 3 coach, to be used for new trailing vehicles.

RC013 The results of the benchmark comparison should firstly demonstrate that the measured coefficients are within a specified tolerance of the benchmark value. Secondly, it should be used to indicate any systematic bias in the aerodynamic rolling moment coefficients compared with the reference results. Adjusted aerodynamic rolling moment coefficients should then be determined with an allowance for this bias. These adjusted coefficients would be the basis for the subsequent interpolation and analysis.

2.2 Outline of the code of practice

RC014 The following list sets out the method and criteria for benchmarking. This is followed by a series of recommendations concerning specific aspects of wind tunnel tests including requirements for:

- a) the scale and blockage
- b) the wind tunnel
- c) the train model
- d) the embankment model
- e) instrumentation
- f) data acquisition
- g) data processing
- h) the scope of the parameters to be determined by the wind tunnel tests
- i) the interpolation of results.

RC015 Recommendations are also made for competency requirements of those involved in carrying out the wind tunnel tests, quality assurance procedures, records and for review and audit of the experimental data that has been obtained.

2.3 Detailed specification for wind tunnel tests

2.3.1 Benchmarking method and criteria

RC016 The benchmark test should be conducted using the same techniques, configurations, modelled wind conditions, equipment etc as the tests of the new vehicles. The benchmark vehicle for leading vehicles is the Class 390 leading vehicle plus a dummy second vehicle with geometry and dimensions as specified in Appendix D. The benchmark vehicle for trailing vehicles is the Mark 3 coach with two dummy vehicles with geometry and dimensions specified in Appendix E.

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- RC017 The results of the benchmark tests should be compared with the benchmark values set out in Table 2.

Yaw angle, ψ	Benchmark value for a Class 390 leading vehicle		Benchmark value for a Mark 3 trailing vehicle	
	$\bar{C}_{R,bmk}$	$\hat{C}_{R,bmk}$	$\bar{C}_{R,bmk}$	$\hat{C}_{R,bmk}$
15°	0.21	-	0.15	-
30°	0.46	-	0.35	-
45°	0.69	-	0.57	-
60°	0.81	-	0.69	-
75°	0.81	-	0.75	-
90°	0.73	0.38	0.75	0.38

Table 2 Benchmark level ground aerodynamic rolling moment coefficients

- RC018 These coefficients are derived from BMT results file 43355 rep2v2_Appendix E_Level ground results, located on West Coast Project library CD.
- RC019 Exact agreement is not expected (for example, due to the specified tolerances in wind conditions, differences in the wind tunnels and differences in test facilities). It is, however, necessary to limit the degree of discrepancy and to allow for any systematic bias as explained in RC020.
- RC020 The measured test results should firstly be compared with the above benchmark values to determine whether the wind tunnel tests are giving results that are within the following tolerances. Note that the values of $\bar{C}_{R,raw}$ and $\hat{C}_{R,raw}$ used in the comparisons below are the values obtained from the benchmark test. The maximum and the mean are determined from each of the yaw angles (ψ) set out in Table 2.

$$\max\left(\frac{|\bar{C}_{R,raw} - \bar{C}_{R,bmk}|}{\bar{C}_{R,bmk}}\right) < 15\%$$

$$\text{mean}\left(\frac{|\bar{C}_{R,raw} - \bar{C}_{R,bmk}|}{\bar{C}_{R,bmk}}\right) < 5\%$$

$$\max\left(\frac{|\hat{C}_{R,raw} - \hat{C}_{R,bmk}|}{\hat{C}_{R,bmk}}\right) < 10\% \text{ for the case of yaw angle, } \psi = 90^\circ$$

- RC021 Max (X) is the maximum value of X derived and mean (X) is the arithmetic mean value of X for yaw angles 15°, 30°, 45°, 60°, 75° and 90°.
- RC022 If the results fall within these tolerances, the test technique is deemed to be an acceptable basis for deriving the required results. If, however, any of these tolerances are not respected then improvements and arrangements should be made to the test techniques so as to respect the tolerances. This could require refinements to the wind profile and turbulence modelling as well as verifications of all model and instrumentation arrangements.

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- RC023 The remaining bias, following any improvements to the test techniques and arrangements, as set out in RC022, should be expressed as ratios which are used subsequently as correction factors during data processing:

$$\bar{k}_{CR_bias} = \text{mean}\left(\frac{\bar{C}_{R,bmk}}{\bar{C}_{R,raw}}\right) \text{ and } \hat{k}_{CR_bias} = \left(\frac{\hat{C}_{R,bmk}}{\hat{C}_{R,raw}}\right) \text{ where } \hat{k}_{CR_bias} \text{ is determined using}$$

the values for the case of yaw angle, $\psi = 90^\circ$.

2.3.2 Model scale and blockage recommendations

- RC024 The required cross section dimensions and wind tunnel velocities of the wind tunnel are determined by the requirements relating to model scale and blockage.
- RC025 All linear dimensions of the model vehicle and model embankments are scaled in the same ratio as the model scale so that geometric similarity is achieved.
- RC026 A reference wind tunnel velocity should be chosen and all tests should be made at similar wind tunnel velocities within a 5% tolerance of this value to achieve:
- $$0.95 < \bar{U}_{raw} / \bar{U}_{ref} < 1.05$$
- RC027 The Reynolds number should be greater than 2×10^5 to ensure flow similarity between model and full-scale flows.
- RC028 B_V should be less than 0.03.
- RC029 B_W should not be so large that the presence of the side walls of the tunnel cause any distortions to the flow around the ends of any leading vehicles, when these are perpendicular to the tunnel, and should be less than 0.75.
- RC030 B_E should be less than 0.2.
- RC031 For example, assuming a test of a three vehicle group ($n = 3$), with vehicles having a full-scale height of 3 m and length of 25 m (hence $A = 75 \times S_l^2 \text{ m}^2$) in a wind tunnel capable of 30 m/s velocity $\bar{U}_{ref} = 30 \text{ m/s}$, modelling embankments of up to 12 m full-scale equivalent height $h_{E,M} = 12 \times S_l \text{ (m)}$, then:
- RC032 From RC027: model scale, if $S_l > \frac{\nu \times \text{Re}}{3 \times \bar{U}_{ref}} = \frac{1}{30.8}$, say $S_l > \frac{1}{30}$

where ν is the kinematic viscosity of air.

- RC033 From RC028: wind tunnel free cross sectional area $A_{WT} > \frac{n \times 75 \times (S_l)^2}{B_V} = 8.33 \text{ m}^2$

- RC034 From RC029: wind tunnel width $W_{WT} > \frac{n \times 75 \times S_l}{3 \times B_W} = 3.33 \text{ m}$

- RC035 From RC030: wind tunnel height $h_{WT} > \frac{12 \times S_l}{B_E} = 2 \text{ m}$

- RC036 Note that the residual effects of blockage should be accounted for by applying blockage corrections as described in RC074.