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Information Note

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1. Introduction

Following the issue of Report 4: Appraisal Report, Transport Scotland have requested Faber Maunsell to prepare a brief report on the beneficial effects of windshielding for the bridge options. In this report we also provide some background on the different types of windshielding and examples of bridges which have windshielding.

2. Background

The recommended design of the bridge produced at the end of the Setting Forth project in 1996 included windshielding so as to improve the availability of the crossing to wind susceptible vehicles (WSVs). These recommendations were taken forward in the Forth Replacement Crossing Study and were included in the bridge deck cross section included in Report 4 (Refer to Figure 1).

Windshielding is intended to provide a degree of protection to wind susceptible vehicles. WSVs include Luton vans, and similar high sided vehicles (especially when unladen), caravans and other trailers, and motorcycles.

The windshielding will typically comprise longitudinal rails and planks and wind tunnel tests carried out during the Setting Forth Studies considered equally spaced longitudinal planks of between 250mm and 500mm depth to give an overall porosity of between 45% and 50%.

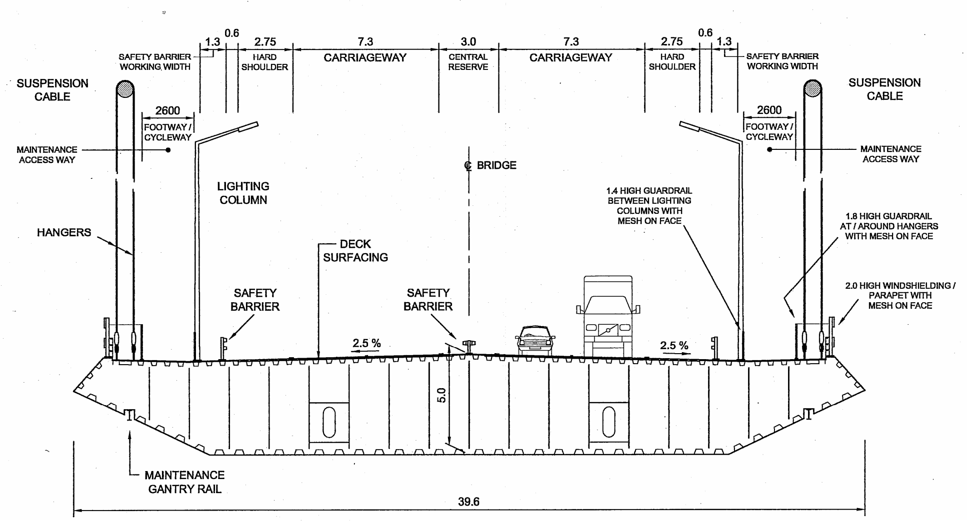


Figure 1: Bridge Deck Cross Section (Report 4: 2007)

A significant amount of study work was carried out in the mid 1990s into providing windshielding on the proposed Second Forth Road Bridge as part of the Setting Forth project. The study work encompassed the following:

- Assessment, in general terms, of the effects of high winds on vehicles and assessment of the critical threshold wind speeds for the imposition of traffic control measures.

- Assessment of the wind climate at the Queensferry site on the Firth of Forth and examination of the level of disruption to traffic on the existing bridge caused by high winds.

- Assessment of the efficacy of windshielding in reducing adverse effects of high winds on vehicles and identification of suitable configurations of windshielding for the Second Forth Bridge

- Analysis of the numbers of hours of restrictions to traffic likely to occur on a shielded and an unshielded bridge, and hence estimation of the benefits to traffic of the windshields

- Proposal of operating systems for both a shielded and unshielded bridge

- Calculation of the structural implications of installing windshielding and estimation of its cost

- Assessment of the overall costs and benefits of windshielding and final recommendations

It is not the intention to summarise all this work, but to identify some salient points and issues relating to the provision of windshielding.

3. Types of Windshielding

The major variables involved in the design of windshielding are discussed in turn below.

3.1 Continuity

Observations on some existing bridges including the first Severn Bridge detected that traffic experiences additional difficulties as it passes the main towers. It was suggested that localised windshielding at the towers would reduce these problems. Some research conducted in connection with the Queen Elizabeth II Bridge at Dartford lent weight to this theory and localised shielding has been installed both on this bridge and the first Severn Bridge. However, discontinuous shielding of this nature only serves to mitigate vehicle handling problems at the towers and does not mitigate vehicle handling problems on the rest of the crossing. It should be noted that both these major strategic crossings are still subject to frequent delays and disruption due to high winds.

Therefore it can be seen that continuous windshielding will provide benefit for all vehicles using a bridge crossing in an area exposed to high winds.

3.2 Height and Porosity

There is generally a trade-off between the effectiveness of the windshielding and its structural implications and cost. In simple terms, a higher, less porous barrier will be more effective in shielding traffic from the winds but will require more material in its own right and will also impose larger lateral loads onto the bridge deck structure, towers and foundations. As a result, the bridge structure will need to be stiffer to maintain aerodynamic stability in long spans.

Research on bridges of approximately 450m span has shown that a 3 metre high barrier with horizontal rails providing 50% porosity offers a reasonable compromise. The 3 metre barrier reduces wind overturning moments on high-sided vehicles by between 40 and 60 per cent.

In broad terms, the effects of the windshields on the bridge aerodynamics become more severe as the span length increases. The bridge forms considered for the Forth Replacement Crossing all have spans considerably in excess of 450m and so the aerodynamic effects are potentially the dominant aspect. Therefore, both 3m height, 50% porosity and reduced 2m height, 45% porosity windshields were assessed during the Setting Forth studies in order to obtain a comparison of the effects of the different types of windshielding on the aerodynamic performance of the bridge.

Windshielding can be provided at a variety of angles to the vertical including inward inclined and outward inclined angles. Various angles were considered at the Setting Forth stage but the most beneficial for this bridge was the vertical windshield.

3.3 Material

On a long crossing, continuous windshielding becomes a significant weight in its own right. Not only do the initial capital costs need to be addressed, but also the weight imposed and the need for future maintenance, especially in a harsh estuarine environment.

Of the possible materials, aluminium and glass reinforced plastic offer major benefits in terms of their light weight and low maintenance compared to steel.

3.4 Windshielding on Other Bridges

3.4.1 Europa Bridge

The Europa Bridge in Austria is an 820m long steel composite structure which is, at its highest point , 190m above the Sill Valley floor. Traffic is protected from the worst effects of wind by a solid shield 1.8m high on each side of the structure. This was one of the first examples of a bridge where it was considered vital to maintain reasonable driving conditions even during very high winds and so windshielding was incorporated into the design.

3.4.2 Queen Elizabeth II Bridge, Dartford

The Queen Elizabeth II Bridge is a cable stay bridge and it carries four lanes of southbound traffic on the M25 over the Thames at Dartford. The total length of the crossing is approximately 3km and at midspan is 60m above the river. Although recommendations were made to provide continuous windshielding, only localised shielding was provided at the main towers.

It should be noted that several times since opening, the bridge has had to be closed to traffic due to high winds or speed restrictions have been imposed.

3.4.3 Second Severn Crossing

The Second Severn Crossing is a total length of 5.1km and its main cable stay structure has a main span of 450m and a navigational clearance of 45m above high water. The entire length of crossing has windshielding 3m high and 50% porosity. This was a conscious decision to provide protection to traffic on this strategic route, which suffered closures of the first crossing during periods of high wind.

Figure 2: Second Severn Crossing Windshielding – Approach Spans

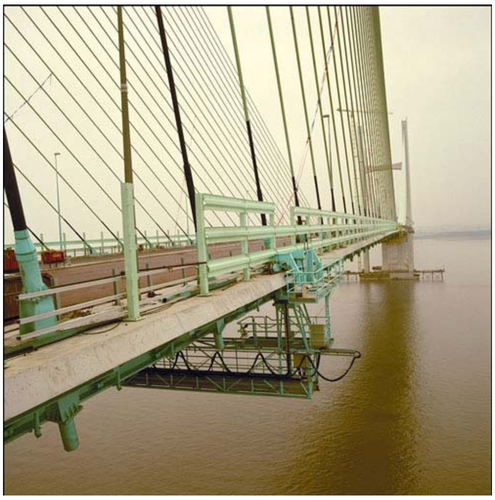


Figure 3:Second Severn Crossing Windshielding under construction

It is understood that the Second Severn Crossing has never been subject to traffic diversions due to high winds since its opening in 1996.

3.4.4 First Severn Crossing

The first Severn Crossing is a suspension bridge with a main span of 987m. As mentioned in section 3.1 above, the first Severn Bridge does have some windshielding, local to the main towers. This is intended to counter the effect of vehicles passing into their shadow and out again.

Figure 4: First Severn Crossing – localised windshielding

The bridge is closed frequently due to high winds (for example, the bridge was closed 8 times between 2 November 2003 and 8 February 2004). The current procedure under high winds includes closure to all traffic when wind gust speeds reach 44mph with forecast predicting increasing wind speeds to over 66mph within the next hour.

3.4.5 River Boyne Bridge

The River Boyne Bridge in the Republic of Ireland is an asymmetric cable stay bridge with a single pylon and a main span of 170m. The superstructure is 20m above the adjacent ground. Continuous windshielding was provided 2.1m high inclined at an angle of 20 degrees to the vertical and porosity of about 50%.

3.4.6 West Link Bridge

West Link Bridge is a viaduct located in Dublin. Continuous windshields were added retrospectively to the bridge.

3.4.7 Millau Viaduct, France

Millau Viaduct in the south of France is approximately 2.5km long with maximum spans of 342m and the deck level is approximately 250m above ground level. Windshielding inclined towards the deck is provided full length of the viaduct.

4 Analysis of Wind Climate at Queensferry

A detailed analysis of the wind climate at Queensferry was carried out during the Setting Forth studies. It was clear that the Forth Road Bridge site was exposed to stronger winds than the Severn Bridge site. The analysis showed that over the period from 1973 to 1991 the site was subject to gale force winds (i.e. Beaufort force 7, 28 to 33 knots or above) for an average of 400 hours per annum. The majority of gales (70%) occur between November and March, but severe storms can occur during the summer months. The direction of gale force winds was predominately in a narrow 90° sector from the south west, covering 85% of all gales. Given the orientation of the proposed bridge lying approximately SSW-NNE, it is evident that southbound traffic will be much more affected than northbound.

Based on the wind data, further analyses were carried out during the Setting Forth studies to determine the need for, and advantages of, windshielding. The anticipated number of restrictions per annum predicted by the studies is given in the table below.

Restriction	Frequency of Occurrence (No. per annum)		
	No Windshielding	3m high barrier	2m high barrier
Warning signs and 40mph speed limit	58	13	17
Diversion of WSVs in both directions	22	2	3 - 4

The table above was produced during the Setting Forth studies and is provided to show the comparative performance of the 2m and 3m high windshielding.

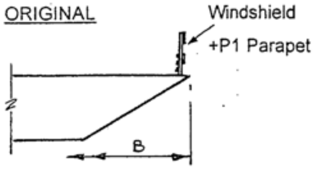
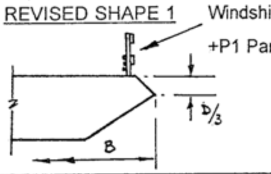
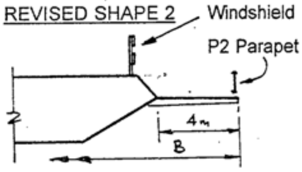
It can be seen that there is a significant improvement in service which may be gained by windshielding the new bridge, with the 3m barrier providing a slightly better level of protection than the 2m barrier. The 2m barrier was nevertheless very effective itself. It is noted that the complete closure of a shielded new bridge will be extremely rare, and that the conditions necessary to induce such a decision will be so severe as to make driving anywhere on the road network hazardous.

5 Detailed Examination of Windshielding for the Forth Replacement Crossing

As noted above, the addition of windshielding increases the wind loading on the bridge and, more importantly, reduces the potential aerodynamic stability of the bridge. A factor called the ‘reduced velocity’ is used as a measure of aerodynamic stability, which is determined by wind tunnel testing:

$$\text{Reduced Velocity} = \frac{\text{wind speed to produce instability}}{\text{(natural frequency x width) of bridge}}$$

Wind tunnel tests carried out for the Second Severn Crossing and for Setting Forth indicated that the Reduced Velocity for a streamlined box section deck was typically 7 (or more) without windshielding, but reduced to 4.5 with 3m windshielding. Aerodynamic instability can occur if the reduced velocity determined by the details of the bridge design and the site exceeds that determined by wind tunnel tests. The results of the wind tunnel tests from the Setting Forth Studies are presented below:

Edge Shape	Windshield Height	Critical Reduced Velocity $U_c/B N_\theta$		
		0°	+2½° ◆	+5°†
ORIGINAL 	P1 only	6.44	5.16	5.74
	2m	4.8	4.38	5.54
	3m	4.5*	4.28*	-
REVISED SHAPE 1 	2m	5.34	5.54	7.64
	3m	4.92	5.68	8.26
REVISED SHAPE 2 	2m	4.87	6.38	9.64

Notes

◆	:	2½ wind inclination:	U_c taken as 80% of horizontal wind case
†	:	5° wind inclination:	U_c taken as 50% of horizontal wind case
*	:	Results from Second Severn Crossing	

Figure 5: Results of Wind Tunnel Test from Setting Forth Studies

The natural frequency of both the suspension bridge and cable stay options for the Forth Replacement Crossing will be less than that for the 450m span Second Severn bridge. The wind speed at Forth is also higher and these factors therefore make the effect of adding windshielding more critical for the Forth Replacement Crossing.

The study into windshielding was carried out during the earlier stages of the Setting Forth study period, when a number of different bridge options were being pursued. The highway cross section at that time accommodated a dual two lane carriageway with 2.6m wide hard shoulders, with a preferred arrangement of providing maintenance access to the bridge via an access train through the deck (similar to that used on Second Severn). This gave an overall deck width of 31.8 metres. It was concluded at that time that this width was insufficient to accept any windshielding on the new Second Forth Bridge.

From the above definition of reduced velocity, it can be seen that the reduced velocity can be reduced by either increasing the natural frequency or by increasing the deck width. It is difficult to make a large change to the natural frequency of a long span bridge, and so the most effective method of achieving aerodynamic stability is to increase the deck width. During the Setting Forth studies it was found that, for the suspension bridge, the bridge deck width needed to be increased to approximately 36m in order to accommodate 2m high windshielding. This increase in deck width led to an increase in the cost of the bridge during the Setting Forth studies. The additional width was used to accommodate maintenance access outside the carriageway, leading to the bridge cross-section recommended at the close of the studies. This width has subsequently increased to approximately 40m to accommodate the requirement for pedestrian access and to satisfy current legislation regarding widths of hard shoulder, central reserve and working widths to safety barriers.

With the continuing experience of operating and maintaining the existing Forth Road Bridge, it is evident just how useful the separated footway/cycletracks are at providing essential maintenance access. Although there is, in theory, a possibility of reducing the deck width if the windshields are omitted, we do not believe that this option would be attractive from a maintenance point of view.

For the cable stay bridge option, with the span arrangement of 650m and 600m, the results of the wind tunnel tests from the Setting Forth studies indicated that windshielding with a height of 3m and porosity of 50% could be accommodated on a bridge deck with a width of 31.8m. Since the cable stay bridge option was discarded in favour of the suspension bridge at the Setting Forth stage, this higher windshield was not pursued. The ability of the cable stay bridge option to accommodate the 3m high windshielding has not been verified during the present Forth Replacement Crossing Study. The current envisaged deck width of 40m is greater than the deck width studied in the wind tunnel tests and this will improve the aerodynamic performance of the bridge. It is recommended that wind tunnel tests are carried out at the next stage of the design to optimise the design of the windshielding.

The cost of providing 2 metre high windshielding on the two edges of the bridge would be approximately £8.5 M. This includes for the full length of the main bridge, approach viaducts and the viaduct over St Margarets Marsh. This cost assumes that the current deck layout is similar to that shown in Figure 1 of this file note (also as included in Report 4). If the decision is taken, during the design stage, to remove the access ways or the hard shoulders this may reduce the width of the deck to below the critical width (approximately 36m for the suspension bridge or 31.8m for the cable stay bridge) for ensuring aerodynamic stability. If the width becomes less than this critical width, it would become necessary to widen the deck to accommodate the windshielding resulting in a significant additional increase in cost.

6 Conclusion

Windshielding will be of great benefit to the users of the Forth Replacement Crossing. Windshielding has been used in various forms on may bridges throughout the UK and the rest of the World. On the Second Severn Crossing there have been no reported incidences of WSVs being diverted during high wind. However, the First Severn Bridge and Dartford Bridge, which have localised shielding adjacent to the main towers, are frequently closed to WSVs.

Windshielding on bridges, particularly long span bridges potentially has an adverse effect on the aerodynamic performance of the bridge. These effects were tested during the Setting Forth Studies using wind tunnel tests based on several deck edge shapes and bridge spans. It was concluded that the deck width needed to be a minimum of 36 metres wide in order to provide adequate aerodynamic stability. In the Forth Replacement Crossing Study, the proposed deck, which includes hard shoulders and maintenance access ways, has a width of approximately 40m.

For the suspension bridge option, to achieve a balance between adequate shielding for WSVs and adequate aerodynamic stability, the Setting Forth studies recommended 2m high windshielding with a porosity of 45%. To date, this windshielding configuration has been adopted throughout the Forth Replacement Crossing Study for both the suspension and cable stay bridge options.

For the cable stay bridge option, the Setting Forth studies suggested that the windshielding could be 3m high. Since the cable stay bridge option was discarded in favour of the suspension bridge at the Setting Forth stage, this higher windshield was not pursued. It is recommended that studies be undertaken at the next stage of design to optimise the design of the windshielding.