Summary

City, University of London (CUoL) was appointed by Highways England (HE) to assess the vehicle driving stability on the Orwell Bridge under high winds. The project included the development of detailed bridge and vehicle numerical models for the assessment of the traffic stability in the Orwell Bridge. The study took place from October 2018 to October 2019

The project is organised in five work packages (WP), which are described in detail in the full report and are summarised below:

WP 1. Development of the finite element (FE) model of the Bridge based on the engineering drawings provided by HE.

WP 2. Definition of the Orwell Bridge environment, including the simulation of the pavement irregularities and the wind velocity time-histories for the dynamic analysis.

WP 3. Definition of the aerodynamic forces on the deck of the Bridge and on the vehicles by means of two- and three-dimensional (2D and 3D) computational fluid dynamic (CFD) analyses.

WP 4. Development of static vehicle models and assessment of the driving stability for different types of vehicles and wind incidence angles.

WP 5. Development of a wind-vehicle-bridge dynamic model and assessment of the driving stability in the Orwell Bridge for different types of pavement and vehicle characteristics.

The work started with the development of a detailed finite element (FE) model of the Orwell Bridge based on the engineering drawings of the structure (WP 1). A full analysis of the three-dimensional (3D) vibration properties of the Orwell Bridge was conducted and used in the dynamic analysis of WP 5. The pavement irregularities and the turbulent wind velocity histories in the Bridge were simulated from the provisions given in ISO 8608 [1] and Eurocode BS-EN1991-2 [2], respectively (WP 2). The randomness of the wind and the pavement profiles was considered by generating 5 aleatory records for the dynamic analysis conducted in WP 5. The study continued with a computational fluid dynamic (CFD) analysis of the aerodynamic actions on the deck and the vehicles in WP 3. The dimensions of typical modern high-sided vehicles in the UK were proposed based on a survey of vehicle manufacturers. A two-dimensional (2D) CFD model was conducted to understand the aerodynamic effects of the variable section of the deck above the River Orwell, the bridge parapets and the angle of attack of the wind. The aerodynamic actions on the deck were obtained from this study and used in the dynamic wind-vehicle-bridge interaction analysis from which the vehicle accident risk assessment was performed in WP 5. The results of the 2D CFD analysis showed that the shape of the deck and its parapets can effectively protect the vehicles crossing the Bridge. The potential implications of the wind shielding created by the deck on the vehicles were further explored in a 3D CFD analysis with a high-sided vehicle located on the critical road lane

(the windward one, referred to as Lane 1 in this study). The results indicated the presence of complex 3D vortices shed between the parapets and the vehicles and also downwind, as well as the recirculation of the wind flow between the two box girders. The results of the CFD analysis ignored the incoming turbulence of the wind and considered only the case in which the wind is purely horizontal and perpendicular to the bridge (cross-wind). The results need to be validated by experimental wind tunnel testing in which different angles of incidence and different angles of attack of the wind are considered.

A preliminary assessment of the driving stability risk was conducted in WP 4 from static models of the vehicles based on the equilibrium between the vehicle wheel/pavement forces, the gravity and the wind actions. The goal of the static analysis was to provide a benchmark to the subsequent and more complex dynamic analysis conducted in WP 5. The simplicity of the static analysis also allowed to explore the driving accident risk of different vehicle types and the influence of the wind incidence angle, aspects that cannot be fully included in the available dynamic models. The vehicles considered in the study were: a car, a bus, a large van, a truck and a tractor with a trailer. Two types of static models were developed: a basic 2D model and a full 3D model. A comprehensive parametric analysis was conducted in both static vehicle models, including more than 36,000 static calculations with a wide range of wind incidence angles and mean wind speeds (U). This study confirmed that the vehicles that are more likely to suffer accidents induced by wind are large unladen high-sided vehicles. An important observation of the static analysis is that the most dangerous wind speed direction is not purely transverse to the deck of the Orwell Bridge, as the current operation protocol for this structure implies. Instead, the static analysis indicates that the vehicle velocities for which crossing the Bridge resulted unsafe are reduced by up to 30% when the wind forms an angle between 30° to 70° with respect to the direction of the deck (East-West). Therefore, a wind-directionality safety factor $k_d = 1.3$ is recommended to reduce the critical driving speeds in the subsequent dynamic analysis of WP 5, in which only cross-wind configurations can be considered. Based on the meteorological information publicly available on the site of the Orwell Bridge, which suggests that the most likely direction of strong winds is south-west, the westbound traffic in the south girder would be at higher risk of accidents than the eastbound traffic in the north girder. However, due to the uncertainty of the gust directionality in periods of high winds, it is not recommended to establish the wind protocol based on the direction of the mean wind speed.

A dynamic analysis in which the dynamic interaction between HGVs (critical vehicles), the movement of the bridge, the pavement irregularities and the turbulent wind was performed in WP 5. The analysis considered that the wind is perpendicular to the Orwell Bridge and a safety factor $k_d = 1.3$ is applied to the results to account for wind directionality effects. The reference vehicle used in the dynamic analysis is an unladen high-sided vehicle for which aerodynamic wind actions are given in the literature [3]. These actions on the vehicles are based on experimental testing in which the vehicles studied were not on a bridge. In light of the CFD analysis conducted in WP 3 for the Orwell Bridge it is apparent that the off-bridge bridge coefficients employed here can be conservative because they ignore the wind shielding provided by the Orwell Bridge deck and its parapets. However, in the absence of more detailed wind tunnel testing in the Orwell Bridge, it is recommended to consider the off-bridge coefficients available in the literature. Also on the safe side, it is assumed in the driving safety analysis that the vehicles use the windward lane (Lane 1 in the south girder) to cross the Bridge. The reference analysis also assumes that the adherence between the tyres and the pavement is relatively low and it can represent a situation with wet pavement that is detrimental for the driving stability. The capacity of the driver to steer the vehicle when the instability induced by wind starts is also ignored on the safe side. The road is considered to be of "very good" quality in terms of the pavement irregularities according to ISO 8608 [1].

A parametric analysis was conducted in the reference case by increasing gradually the intensity of the wind and the vehicle driving speed until accidents are observed in the Bridge. The results are presented in the form of Critical Wind Curves (CWC) that give for each wind speed the critical vehicle speed above which accidents occur. Figure 1 shows the reference CWC in the Orwell Bridge and summarises the assessment of the vehicle accident risks conducted in this study. The thick green line in this figure represents the arithmetic mean of the results obtained with 5 pavement and wind records (thin lines in the figure). The results show that almost all the combinations of wind and vehicle speeds that are allowed by the current protocol in the Orwell Bridge result in safe driving considering the reference case, which is one of the most detrimental situations that can reasonably occur in the Bridge. However, based on the different conservative assumption adopted in the analysis, increasing the current wind speed limits is not recommended. The reference CWC also shows that reducing the driving speed of high-sided vehicles can reduce the risk of accidents in the Bridge.

Different studies were conducted by modifying several aspects of the reference case in order to explore the influence on the driving safety of the pavement conditions, the vehicle characteristics and the bridge shielding. The results indicate that the pavement adherence is beneficial for the driving stability and that the amplitude of the pavement irregularities in the Orwell Bridge can also affect significantly the vehicles' safety. It is recommended to maintain the quality of the pavement in the higest standards in the entire length of the Bridge, particularly on the road lanes that are closest to the edge parapets (Lanes 1 and 4). The study has verified that the weight of the vehicle has a positive stabilising effect. However, if unladen high-sided vehicles cannot be prevented from accessing the Bridge in windy days it is recommended to consider their minimum (unladen) weight in the calculation of the CWC. It was also observed in this work that the arrangement of the cargo in the vehicle does not affect significantly its driving safety. The influence of the exposed area of the vehicle resulted more important than the position of its load but its effect is not very significant for the wind speeds in which the Bridge is open to traffic.

Finally, the aerodynamic actions of the vehicle on the Orwell Bridge obtained from the 3D CFD analysis were considered instead of those obtained from experimental testing on vehicles outside the Bridge. The results show that the shielding of the existing parapets is able to reduce significantly the risk of accidents in the Bridge. However, the numerical results need to be supported by wind tunnel testing in this structure.

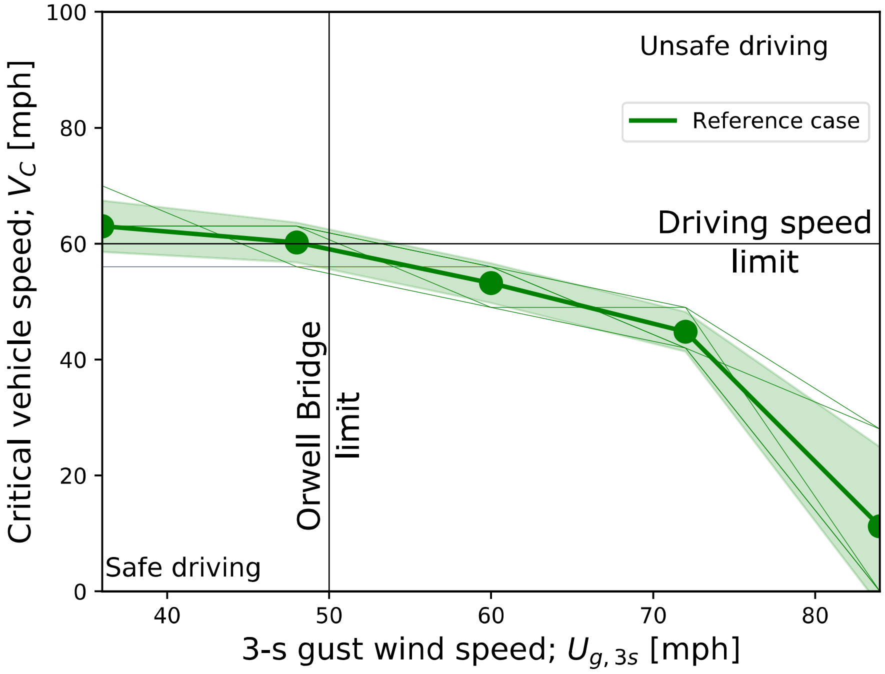

Figure 1: Reference CWC in the Orwell Bridge. The thin lines represent the results with each pavement and wind record, the thick line is the average and the colour band around it represents ± one standard deviation.