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A moving-model and side-wind-tunnel methodology with full-scale validation for investigating the crosswind-stability of vehicles on bridges

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SUMMARY:
The functionality of a novel 1:15 scale moving-model and side-wind-tunnel methodology for investigating crosswind stability of vehicles on bridges is demonstrated. Comparison to full-scale measurements on the Lysefjord Bridge are encouraging, and initial insight into complex aerodynamic interactions is presented.

Keywords: crosswind stability, heavy vehicles, bridge aerodynamics

1. INTRODUCTION

A multi-disciplinary approach – combining wind engineering and vehicle aerodynamics – is being developed for investigations into the stability of vehicles operating in extreme crosswind conditions. In this case, heavy vehicles traveling over a 56 m high bridge across a Norwegian fjord that could encounter wind gusts of up to 40 m/s. Potential changes to the climate and weather conditions could result in increased occurrence of extreme wind events, in addition to ever increasing road usage and infrastructure development. Crosswind exposure and vehicle-infrastructure interaction are inherently transient, non-stationary aerodynamic events that require novel scaled experimental methodologies and full-scale measurements for realistic, representative aerodynamic investigations.

In this work, a new configuration of the moving-model facility in DLR Göttingen is presented. Originally intended for high-speed-train and tunnel interaction, the test-section has been modified to include a 1:15 scale model of the Lysefjord Bridge (Fig 1a.), and a generic truck model within the side-wind tunnel module section (Fig. 1b, 1c, 2). Previous work on passenger automotive-vehicle crosswind-stability over flat-ground in the facility (Bell et al., 2020) has

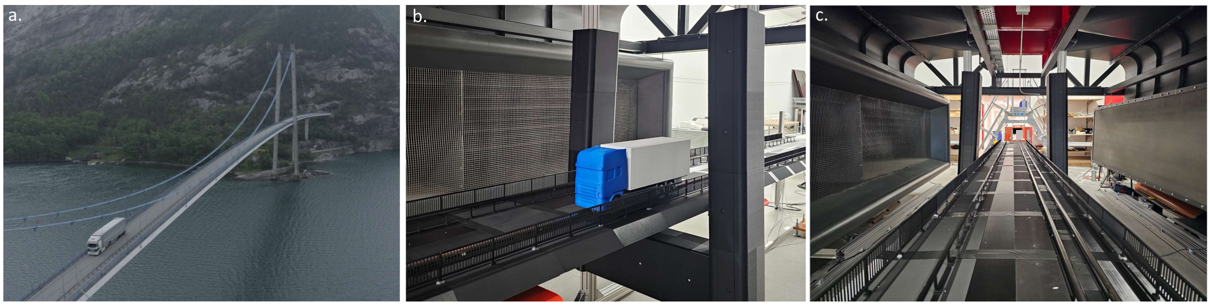

Figure 1. a. Lysefjord bridge in Norway, b.,c. Moving-model and side-wind setup at DLR Göttingen

identified transient characteristics (not able to be modelled in traditional, quasi-steady wind-tunnel experiments), as well as agreeable validation with full-scale measurements in BMW Aschheim side-wind facility (Bell et al., 2021). Here, the scaled moving-model experiments are validated against novel full-scale measurements taken by the University of Stavanger on the Lysefjord bridge, where surface pressure and ultrasonic anemometers measure real-world aerodynamic characteristics (Daniotti et al., 2025a,b; Tolo, 2025; University of Stavanger, 2025). This work represents the proof-of-concept, whilst in the future, the aim is to tune the test-section in an attempt to represent the oncoming and local flow (magnitude, turbulence intensity and length-scales, frequency spectra and gust profiles) experienced by the bridge (and to which the vehicle is exposed to), as well as their effects: transient surface pressure on the bridge. Additional, real-world validation is planned, with measurements on an operational truck loaded with the DLR FR8-LAB – a measurement-equipped shipping container (Bell et al., 2024). Transient pressures and inferred global forces can be compared to measurements made on-board the scaled moving-model truck in the experiments. The validated methodology will then be utilized for optimization and assessment of bridge geometries, infrastructure effects (e.g. towers), engineering solutions like wind fences, and safety operational guidelines.

2. EXPERIMENTAL METHODOLOGY

The model bridge contained 20 differential-pressure sensors (Endevco 8510-B, ±6.89 kPA, 5000 Hz). A reference pitot-static tube was located 400 mm above the bridge. The model truck had an on-board data acquisition system (Teensy 3.6 microcontroller) with 24 Freescale ±7 kPa 14-bit resolution @3500 Hz, an ADXL326 ±16 g accelerometer and phototransistor that measured two pairs of light-emitting diode (LED) strips embedded in the bridge to locate the measurement in space (Bell et al., 2020). In the experiment, the model truck is accelerated by a catapult system, rolls freely on rails through the test section, ending in a braking tank.

The moving-model side-wind methodology enables multiple aspects of crosswind exposure to be simulated. Wind perpendicular to the bridge with zero vertical component and a turbulence intensity of 3-5 % can be generated. The real bridge sees up to 35 % turbulence intensity (Daniotti et al., 2025b) but time-scales are important: large scale fluctuations longer than the vehicle-bridge crossing duration don't require unsteady simulation. Entering/exiting the cross-

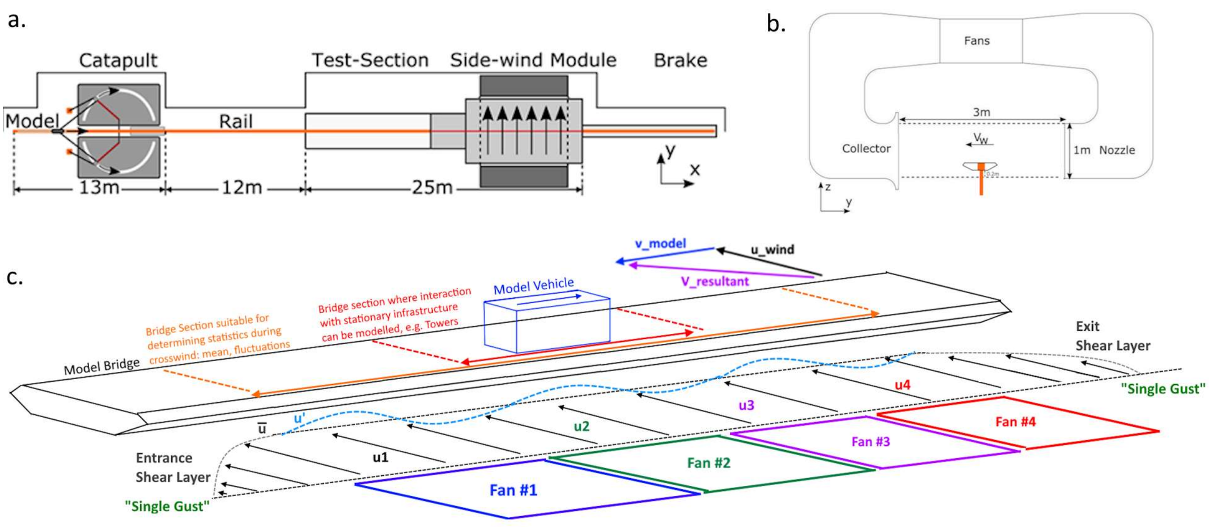

Figure 2. a. Moving-model facility, b. wind-tunnel section and, c. crosswind simulation illustration

wind can represent individual gust exposure. Statistics can be obtained during the majority of the 5 m bridge-model span, where interaction with stationary infrastructure like bridge towers can also be modeled. Further variation in gust profile or wind fluctuation are also achievable with control of the 4 individual fans. The horizontally asymmetric bridge (due to a footpath on the Western side) can be mounted with vehicle moving in both lanes, and horizontally rotated in the test section, to model all 4 possible wind and vehicle direction combinations.

3. RESULTS

Surface-pressure on the 1:15 scale moving-model (MM) results at 10 m/s wind velocity (Reynolds number, based on bridge width, $Re_W = 5.5x10^5$) show reasonable comparison to the full-scale (FS) bridge from a 1-hour sample with moderate winds of 10 m/s ($Re_W = 8.2x10^6$). These results are presented as vectors of the coefficient of pressure, C_P, in Figure 3 and Table 1 for selected locations. A difference is the pressure on the lower windward surface (B3), which is $C_P = 0.5$ for MM and $C_P = -0.4$ for FS. This is considered to be due to the minor angle of attack in the natural wind. The real bridge exhibits wider variability due to natural wind fluctuations. To explore this, the standard deviation from raw FS pressure signals (at 25 Hz sampling frequency) and 1 Hz Hi-pass filtered are presented in Table 1, the later of which are much more comparable to the MM, due to the removal of large-scale fluctuations in FS not reproduced in the MM experiment.

The transient surface pressure experienced by the bridge during crosswind exposure and as the moving vehicle (20 m/s, $Re_W = 2.3x10^5$, where a full-scale truck at 50 km/h $Re_W = 2.4x10^6$) passes over the pressure measurement-position is presented in Figure 4. The pressure coefficient C_P is calculated using the vehicle speed, wind speed and resultant, ($C_{P,V}$, $C_{P,W}$, & $C_{P,R}$ respectively). The moving vehicle generates a large transient positive-pressure, followed by a large under-pressure and then fluctuations in its wake; clearly visible with no crosswind (Fig 4a). During crosswind (Fig 4b), there is high fluctuating windward-pressure (B1), low lee-ward pressure with coherent fluctuations (B12) and lower, more random fluctuating pressure on the upper surface (B15). The bridge during crosswind and vehicle passing exhibit signs of both (Fig. 4c), however, not with simple super-position, indicating complex interaction. Transient pressures on the moving-truck (Fig. 5) show the acceleration of the model, complex, unsteady interaction with the crosswind (t=1.3-1.5s), and local effects of the tower legs (t=1.4s).

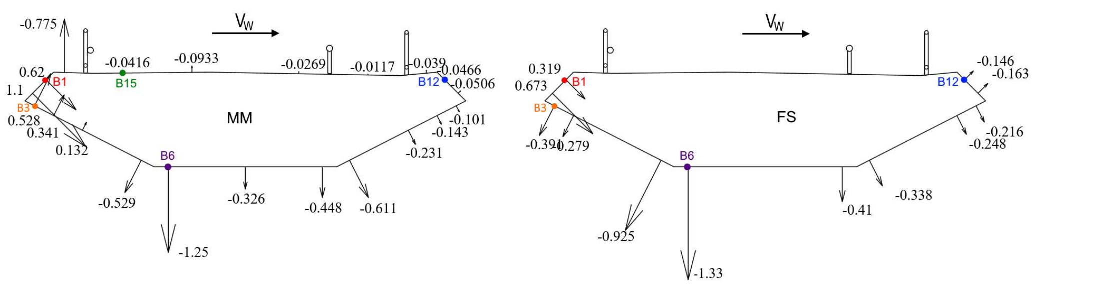

Figure 3. Average pressure (C_P) on moving-model-bridge (MM), and full-scale-bridge (FS).

Table 1. Mean and fluctuating pressure for MM and FS at specific measurement positions

Position	$MM : \bar{C}_P$	$MM : \sigma_{C_P}$	$FS : \bar{C}_P$	$FS : \sigma_{C_{P,raw}}$	$FS : \sigma_{C_{P,1Hz-HiPass}}$
B1	0.62 (0.47, 1.3)	(0.05, 0.09)	0.32 (0.47, 1.3)	(0.66, 0.92)	(0.11, 0.16)
B3	0.53 (-0.87, 0.63)	(0.06-0.09)	-0.39 (-0.1, -0.62)	(0.88, 1.1)	(0.13, 0.19)
B6	-1.25 (-0.98, -1.35)	(0.10, 0.13)	-1.33 (-1.1, -1.6)	(0.68, 0.96)	(0.20, 0.25)
B12	-0.05 (-0.03, -0.36)	(0.048, 0.13)	-0.15 (-0.07, -0.25)	(0.20, 0.37)	(0.04, 0.05)

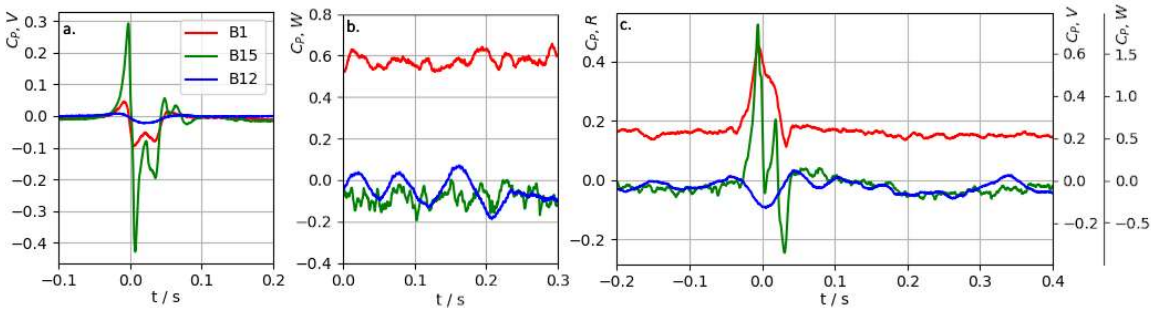

Figure 4. Transient surface-pressure from the bridge with a. a moving vehicle (20 m/s, $Re_W = 2.3x10^5$) with no crosswind, b. during crosswind (12 m/s), and c. moving vehicle (20 m/s) with crosswind (12 m/s).

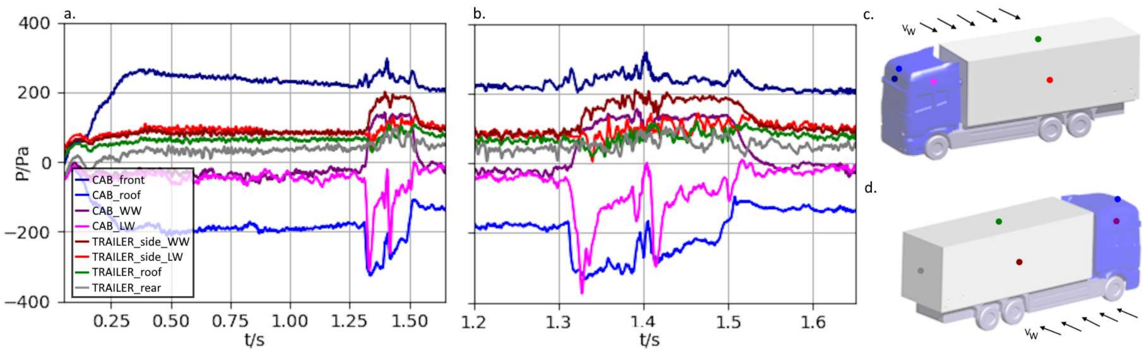

Figure 5. Transient surface-pressure on the moving truck (27 m/s) during a. the entire run, b. crosswind (V_W = 10 m/s) section, at c. leeward (LW) and d. windward (WW) locations.

4. CONCLUSIONS

Functionality of the moving-model and side-wind-tunnel methodology for investigating crosswind stability of vehicles on bridges has been demonstrated with encouraging comparison to full-scale results, and initial insight into complex aerodynamic interactions. Further measurements are planned, with finer tuning and additional variability (e.g. turbulence, yaw/pitch of oncoming flow) and subsequent optimization and assessment of bridge geometry and infrastructure effects such as towers, as well as engineering solutions like wind fences, and safety operational guidelines.

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