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CROSS-STORM project: developing a numerical-experimental procedure for evaluating the risk of accident on road vehicles due to the strong crosswinds generated by a thunderstorm

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1 INTRODUCTION

Thunderstorm outflows generate intense non-stationary winds that might pose significant risk for road vehicles crossing areas where wind field reaches peak intensity (Fig. 1). Baker and Reynolds [1] reported a high incidence of accidents related to intense storm conditions. Zhang et al. [2] demonstrated that sudden changes in wind intensity and direction can generate high-risk scenarios. Despite this, most studies regarding wind-induced accidents are related to the stability of vehicles under generic synoptic wind conditions (e.g., Winkler et al. [3]).

The CROSS-STORM project aims to address this gap by developing a numerical-experimental procedure to evaluate the risk of accidents on road vehicles traveling through strong crosswinds generated during a thunderstorm downburst event. The methodology is articulated in three main phases: defining the wind velocity field during a thunderstorm downburst, calculating the aerodynamic loads on a road vehicle, and evaluating the dynamic response of the vehicle-driver system to wind actions using a driving simulator (DRISMI).

Given the critical role of driver response to storm-induced winds, key scenarios will be simulated in the driving simulator to study the behaviour of the vehicle-driver system. The ultimate goal of the project is to correlate key parameters with specific levels of accident risk.

Most of the approaches developed in the past for the evaluation of risk associated to crosswind acting on road vehicles, especially those applying deterministic wind profiles, focus on the vehicle characterization with respect to the action of the wind.

The CROSS-STORM project instead shifts the attention to the infrastructure, and to the possibility of defining actions that can mitigate the risk of road accidents: from this point of view, the correct evaluation of the atmospheric phenomenon, that is the real incident wind, is fundamental for the definition of targeted actions, such as the installation of windbreak barriers on highly riskiness sections, or the adoption of systems for reducing the maximum travel speed, to be adopted only in certain weather conditions.

The CROSS-STROM project, which began in September 2023 and is planned to last two years, has already made progress in the initial phase.


a) b)

Figure 1, Wind-induced overturning of vehicles due to thunderstorm winds

2 METHODOLOGY

2.1 Downburst Wind Field Model

To accurately simulate the wind velocity field experienced by vehicles during a thunderstorm downburst, the CROSS-STORM project adopts a comprehensive four-step modelling procedure. The first step

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involves modelling the horizontal slowly varying mean wind velocity field of a traveling downburst by using a semi-empirical analytical model [4, 5]. This model integrates three primary downburst velocity components: stationary radial velocity, storm motion, and boundary layer background wind. These components collectively represent the fundamental characteristics of the downburst's horizontal wind field.

In the second step, the model simulates the downburst turbulence wind field. Downburst outflow turbulence is characterized as a non-stationary, non-Gaussian, bi-variate and partially coherent random process. The turbulence properties are derived using an extensive database of real-world downburst outflows, which includes data from anemometric and vertical lidar measurements. Once the turbulent structure is defined, synthetic time histories of velocity fluctuations are generated through Monte Carlo Simulations, utilizing prescribed turbulence spectra and horizontal coherence functions. These spectra and coherence functions are calibrated using full-scale data.

The third step involves reconstructing the non-stationary outflow wind velocity field generated by the thunderstorm downburst. This is achieved by considering the wind components obtained in the previous steps. The resulting model provides a detailed representation of the wind field, incorporating both the slowly varying mean wind velocities and the turbulent fluctuations.

Finally, in the fourth step, the model calculates the time history of the relative wind velocity encountered by a moving vehicle. This calculation considers the vehicle's motion, including its speed and direction, as it travels through the downburst. By determining the relative velocity between the vehicle and the wind field, the model provides the data for assessing the aerodynamic loads on the vehicle and its stability under these extreme downburst wind conditions.

Figure 2 illustrates the simulation of a downburst event and its impact on a moving vehicle using the Xhelaj et al. [4] model. The simulation is conducted within a spatial domain of 15,000 × 15,000 meters, with an equal grid resolution of 25 meters in both directions, and a temporal domain from 0 to 600 seconds.

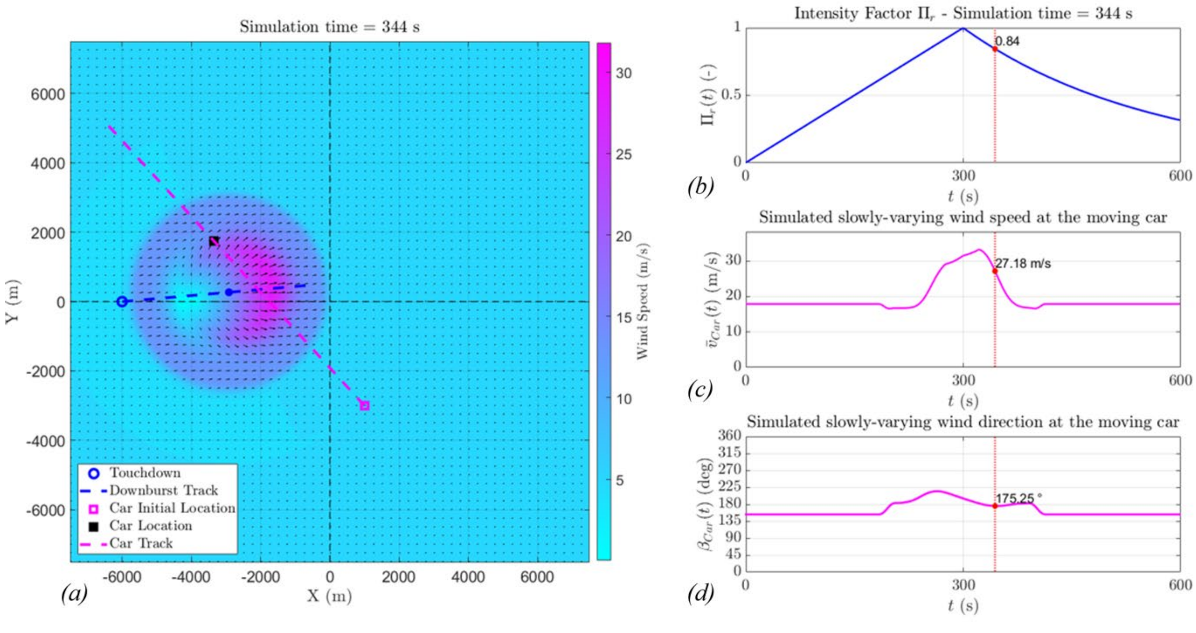

Figure 2, Simulation of the impact of a downburst event on a moving vehicle. Wind velocity filed, downburst and vehicle's trajectory (a). Intensity factor (b). Simulated slowly varying wind speed at the vehicle's location (c). Simulated slowly varying wind direction at the vehicle's location (d).

Key model parameters, including the downburst's touchdown location, maximum radial speed, radial length scale, intensity and decay periods, storm speed, and direction, define the downburst characteristics. In panel (a), the downburst's path over time, based on its translation velocity and direction, is depicted at 344 seconds. The vehicle's kinematics are incorporated by calculating its position over time, considering an initial position (magenta square in Figure 2a). The vehicle moves at a constant speed of 18.75 m/s (60 km/h) and in a fixed direction of 138 degrees from the North, where the Y-axis is aligned with the North, representing the zero-wind direction in meteorological convention. Additionally, the simulation includes a constant boundary layer background wind with a speed of 5 m/s and a direction of 245 degrees from the North. Wind velocities at the vehicle's location are interpolated to determine the wind field impacting on the moving vehicle. Panel (b) shows the downburst's radial intensity factor Π_r over time, highlighting a peak intensity at 300 seconds. Panel (c) depicts the simulated slowly varying wind speed at the moving car, while panel (d) illustrates the simulated slowly varying wind direction at the moving car. The model also includes turbulence components which are not shown in Figure 2 but will be presented in the conference.

2.2 Aerodynamic Loads Calculation

The second part of the project concerns the calculation of the aerodynamic loads acting on a road vehicle due to the strong crosswinds during a thunderstorm. Starting from the simulation of the time history of the thunderstorm wind, the aerodynamic loads can be obtained for a given vehicle if the aerodynamics coefficients that characterise its aerodynamic behaviour are known ([6],[7]). In this project, four different types of road vehicles are considered: an articulated lorry, a double-decker bus, a small lorry, and a saloon car. The selected vehicles are presented in Fig. 3-a. These vehicles are representative of a wide range of sizes and shapes, corresponding to the most diffused vehicle categories across Europe. In this way a comprehensive overview is provided of how different road vehicles behaves when exposed to the severe downburst outflow winds.

To characterise the different vehicles that will be analysed in this study, a dedicated experimental campaign is being conducted in the GVPM wind tunnel of Politecnico di Milano. This campaign aims to generate a uniform dataset of aerodynamic coefficients for the selected vehicles. Because thunderstorm winds are naturally not aligned with the vehicle longitudinal axis, and of course the aerodynamic coefficients depend on the angle of attack of the vehicle, it is therefore necessary to measure the aerodynamic coefficients for the vehicles subjected to crosswinds for a range of angles of attack.

For each vehicle, aerodynamic loads will be measured by a dynamometric balance set inside the model, with a uniform (vertical block profile) wind and standard infrastructure (flat ground). As done in the railway field, the effects associated with scenario (wind profile, viaduct, embankment, etc.) are accounted for by applying specific correction formula to wind speed distribution.

In this way, the aerodynamic loads are calculated based on the wind tunnel data and on scenario characteristics. These loads are the input of the dynamic simulations of each vehicle type. This process is crucial for understanding how these loads affect vehicle stability and control.

2.3 Vehicle-driver Dynamic evaluation

The final part of the methodology involves the study of the stability to thunderstorm of the vehicle, considering the influence that the driver has on the system. The DRISMI driving simulator of the Politecnico di Milano (Fig.3-b) permits to evaluate the dynamic response of the vehicle-driver system to the aerodynamic loads calculated in the previous step. The DRISMI simulator replicates real driving conditions, bringing up the possibility to test how vehicle-driver system responds to crosswinds in a controlled environment, thus allowing for repeatability and reproducibility of the tests. The simulator includes sophisticated controls and feedback mechanisms to accurately reproduce real-world driving conditions.

To evaluate the impact on the behaviour of the system under different conditions, some key scenarios are reproduced. To select the most significant conditions and reduce the number of configurations to be tested with the driving simulator, a preliminary virtual testing phase has been carried out by a multi-body vehicle model.

The vehicle dynamics model integrated within the driving simulator is the multibody software VI-CarRealTime, from VI-Grade: it allows to reproduce each vehicle subsystem (wheels, suspensions, body, steering system, brakes, aerodynamic forces, engine and driveline) and all the forces acting on it ([8]).

Different scenarios have been simulated by using this vehicle dynamics model ([8]), without accounting for the driver. By analysing the results obtained by the virtual testing, the more critical configurations, in terms of accident risk, will be identified and finally tested by the driving simulator.

In the last part of the project, through an experimental campaign with a sample of drivers, the effect of wind conditions on vehicle stability and driver behaviour is studied. These scenarios will help to identify critical factors that influence the accident risk, it can be from the driver side, as for example, driver experience or reaction time, but also from the vehicle side like handling characteristics, mass, load condition, exposed lateral area. Moreover, by analysing the data from the simulator, it will be possible to correlate specific wind parameters with accident risk levels.

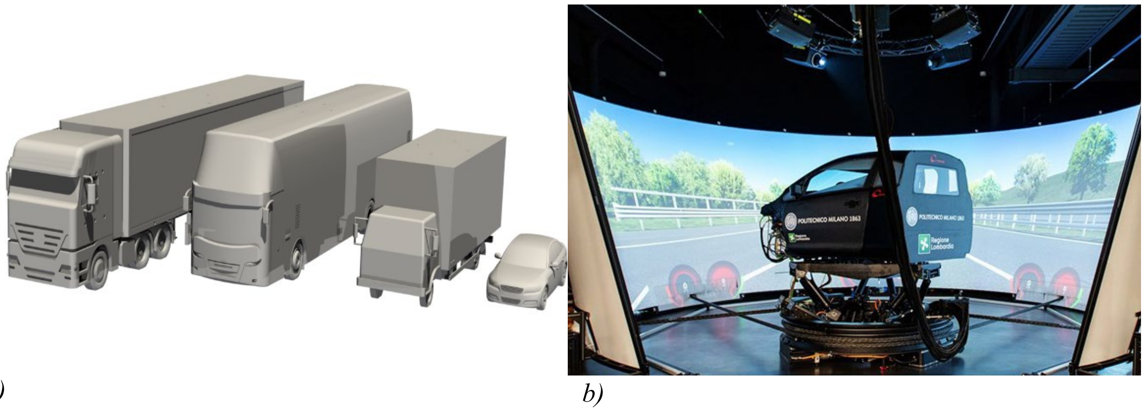
a) b)

Figure 3, (a) Vehicle models to be tested in the wind tunnel tests at Politecnico di Milano Wind Tunnel. From left to right: articulated lorry, double-decker bus, small lorry, saloon car. (b) DRISMI Driving simulator of Politecnico di Milano.

3 CONCLUSIONS

In its first year, the CROSS-STORM project has made significant strides in its initial phases, focusing on the development of a comprehensive numerical-experimental procedure to evaluate the risk of vehicular accidents due to thunderstorm-induced extreme winds. The first phase, involving the simulation of wind fields, is currently underway. The second phase, which includes wind tunnel testing, is scheduled to begin in October 2024. The final phase, assessing vehicle-driver responses using the DRISMI driving simulator, has yet to be initiated. As the project progresses, these efforts will be crucial for enhancing vehicle safety and mitigating the risks posed by severe weather conditions.

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