

Crosswind stability of road vehicles under thunderstorm downburst winds

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SUMMARY:

Because thunderstorm winds can have severe consequences on the risk of accident of road vehicles, this study aims at developing a comprehensive methodology to assess vehicle stability considering also the effect of the driver. The methodology proposed consider three parts: the simulation of the wind field encountered by a car while traveling across a downburst event, the calculation of the aerodynamic forces due to the winds and the evaluation of the dynamic response of the vehicle by means of some risk indexes. In this work an overview of the methodology is presented and preliminary result for a small lorry travelling across a thunderstorm are shown as an example. This work is part of the on-going CROSS-STORM project.

Keywords: crosswind, thunderstorm, vehicle stability.

1. INTRODUCTION

The intense nonstationary winds generated during a thunderstorm may represent a significant risk for road vehicles. In fact, some studies have reported that intense storm conditions and situations in which sudden changes in wind intensity and direction occur are well correlated with the occurrence of accidents (Baker et al., 2009; Zhang et al. 2018) and some hybrid procedures have been developed to study the behaviour of ground vehicles under crosswinds (Cioffi et al., 2022). Even so, in general the studies regarding vehicle stability are made considering just generic synoptic wind conditions.

In this context, the CROSS-STORM aims at developing a numerical experimental procedure to study the stability of a road vehicle travelling across the strong winds generated during a thunderstorm downburst event. The methodology is articulated in three main steps:

1. Definition of the wind velocity field during a thunderstorm downburst,
2. Calculation of the aerodynamic loads acting on the road vehicle.
3. Evaluation of the dynamic response of the vehicle-driver system.

Given the critical role of driver response to storm-induced winds (Cioffi et al., 2023), the most critical scenarios will be analysed in a driving simulator to study the behaviour of the vehicle-driver system.

In this abstract an overview of the methodology is presented and some preliminary result for a small camion travelling across a thunderstorm are shown as an example.

2. SIMULATION STRATEGY

A simulation framework was developed to reproduce the effect of crosswind in thunderstorm conditions on a vehicle. The key elements composing it are:

- A wind model.
- A vehicle model.
- A driver model (if the simulations are performed without a driver in the loop).

At each simulation time-step, the outputs coming from the vehicle model are used to evaluate the crosswind forces and moments acting on the vehicle. This set of aerodynamic forces is then fed as input to the vehicle model, together with the driver's input. Two indexes are computed in post-processing to assess the effective stability of the vehicle under consideration.

2.1. Wind model and aerodynamic loads calculation

The wind velocity field that a vehicle encounters when traveling across a thunderstorm downburst was simulated following the approach developed under the CROSS-STORM project. At first, the horizontal slowly varying mean wind velocity field of a traveling downburst is modelled by using a semi empirical analytical model (Xhelaj et al., 2020) that integrates the stationary radial velocity, storm motion, and boundary layer background wind. Then, the downburst turbulence field, a non-stationary, non-Gaussian, bi-variate and partially coherent random process, is calculated. Finally, the non-stationary outflow wind velocity field generated by the thunderstorm downburst is reconstructed by adding all the wind field components (Xhelaj et al., 2024). Considering the trajectory of the vehicle, wind speed and direction time histories are computed (Xhelaj et al., 2025) and serve as the input to evaluate the aerodynamic forces acting on the vehicle during simulation.

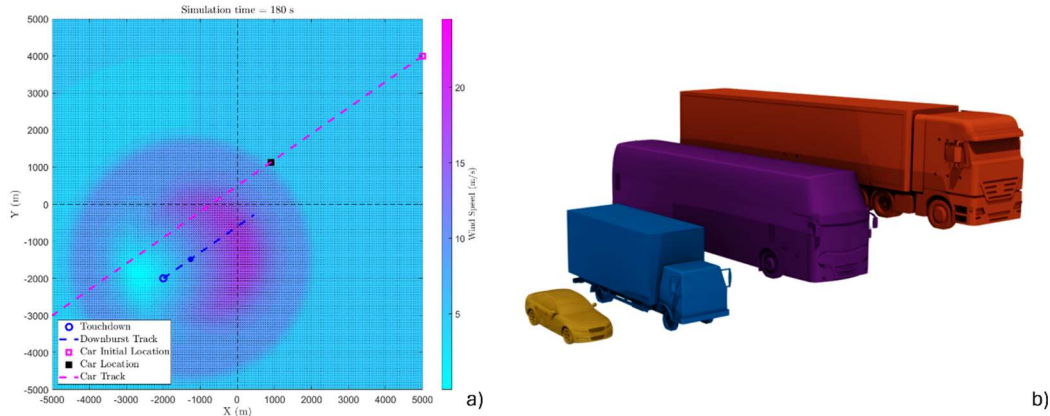


Figure 1. a) Simulated wind field. b) Road vehicles to be studied.

The aerodynamic forces acting on the vehicle are calculated considering the wind velocity along experience by the vehicle along the trajectory, the vehicle speed and vehicle orientation using a quasi-static approach. From the wind velocity and vehicle velocity, it is possible to calculate the relative wind speed and angle of attack of the wind with respect to the vehicle. The aerodynamic loads, it is, forces and moments referred to centre of gravity of the vehicle, are obtained for each time step, considering the corresponding wind relative speed and the aerodynamic coefficients that characterise the vehicle. The aerodynamic coefficients, that depends on the vehicle orientation with respect to the wind, are obtained from wind tunnel test on scale models for the four vehicles considered and shown in Fig 1b).

2.3. Vehicle model and driver

The vehicle dynamics is reproduced using the commercial software VI-CarRealTime. A 14 degrees of freedom multibody model was used to reproduce the dynamics of a given four-wheel vehicle. The particular vehicle can be modelled by defining: the main geometrical and inertial parameters (i.e.: wheelbase, track, mass, moments of inertia, etc.) of the modelled vehicle; the powertrain and brakes characteristics; the tire model (for all the vehicles, Pacejka's Magic Formula with combined friction and relaxation length was used); the suspension and steering system characteristics.

User defined control logics can be introduced directly in Matlab/Simulink thanks to the VI-CarRealTime model interface. The interface defines several channels that can be read and written at simulation time during each time-step. In Fig. 2 it is reported a schematic Simulink model used to perform co-simulation with VI-CarRealTime.

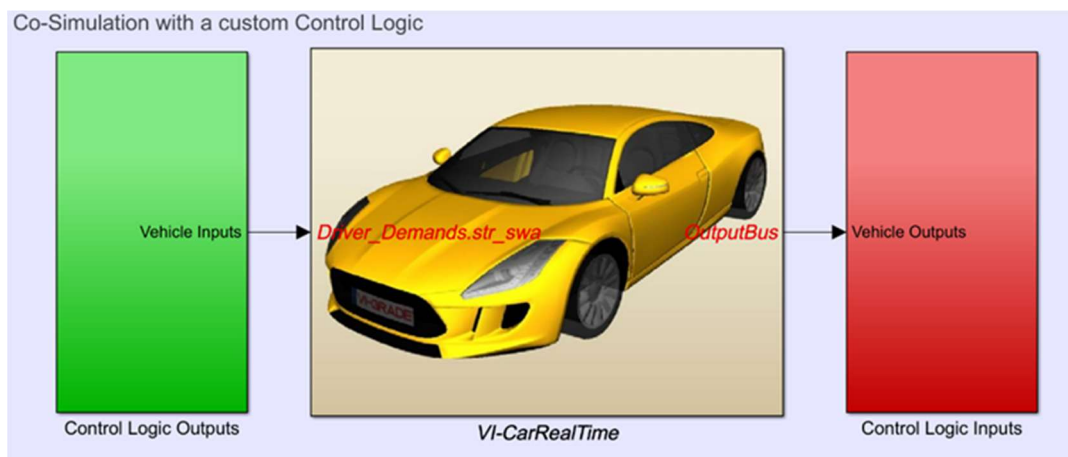


Figure 2. Co-Simulation with Simulink and VI-CarRealTime.

As mentioned in Section 2, it is possible to perform simulations off-line, using Matlab/Simulink and using a Driver-in-the-Loop approach, thanks to the VI-Grade DiM 400 simulator available at the Dri.S.Mi. Laboratory. When simulating off-line, the driver model used is a multiple preview distance one, configured to work with three different weighted preview times. The steering wheel is then controlled in angle by directly imposing the output of the controller.

2.5. Accident indexes

When exposed to a downburst wind, there are two principal kind of events that may occur: the vehicle moves laterally veering out of the lane, producing a lane invasion, or the vehicle rollover. Therefore, to determine the behaviour of the vehicle under thunderstorm winds, two indexes that quantifies the vehicle condition have been defined. The Lane Invasion (LI), consist of computing the remanent lane width considering the lateral displacement of the vehicle. The second index, Normalised Load Transfer (NLT), regarding the rollover risk, and related to the lateral load transfer, is computed as the difference in vertical load between left and right wheel, divided by the total steady state vertical load of the axle, the worst axle is considered.

4. RESULTS

The procedure has been used to simulate the case of an unladen small lorry that travels across the thunderstorm following the trajectory defined in Fig 1.a) at 80 km/h, while the downburst moves at 5 m/s in the opposite direction. The atmospheric boundary wind was set at 5 m/s. In this case the simulation was performed off-line. In Fig. 3 the time histories of the two indexes are shown. LI index overcome the threshold, meaning the lorry goes out of the lane which represent a severe risk of accident, while from the NLT index values a low risk of rollover is obtained.

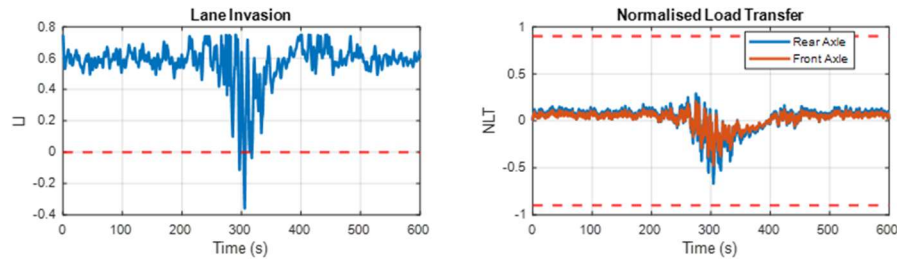


Figure 3. Simulation of an unladen small lorry at 80 km/h under thunderstorm downburst winds. Lane Invasion (LI) and Normalised Load Transfer (LTI) indexes.

7. CONCLUSIONS

In this work an overview of a methodology for the evaluation of vehicle stability under strong nonstationary cross winds generated by a thunderstorm downburst was presented. The procedure is composed by three main steps: the definition of the wind velocity field during a thunderstorm downburst, the calculation of the aerodynamic loads acting on the road vehicle and the evaluation of the dynamic response of the vehicle-driver system.

Future developments of this project include the wind tunnel test to characterise diverse kind of vehicle that are representative of the vehicle universe: saloon car, small lorry, double-decker bus and an articulated lorry.

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