Safety Assessment of a High-Sided Lorry Under Downburst-Induced Crosswinds

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Abstract. The safety of road vehicles can be compromised by crosswinds, particularly during severe thunderstorm conditions. Nevertheless, most studies on vehicle stability typically consider only generic synoptic wind conditions. In this work, a methodology to assess the safety of road vehicles under downburst winds is presented. The workflow includes defining the wind velocity field during the downburst, calculating the aerodynamic loads, and evaluating the dynamic response of the vehicle-driver system. Wind tunnel tests have been performed to obtain the aerodynamic coefficients. Co-Simulation with Simulink and VI-CarRealTime has been used to analyse the behaviour of the vehicle. To include the effect of human driver a driver controller has been defined and validated with the results obtained from the driving simulator. The results demonstrated that a high-sided lorry represents a serious safety risk when exposed to the intense and rapidly varying winds generated during a downburst event.

Keywords: Crosswind, Driving Simulator, Vehicle Stability, Downburst.

1 Introduction

The interest in wind induced accidents of road and rail vehicles has grown in recent years. The risk of accidents is particularly high in presence of bad weather conditions like storms. Windstorms generate intense, nonstationary winds that may constitute a significant risk to road vehicles. With storm trends rising in northern and central Europe [1], while similar patterns are observed in North America [2] and parts of Asia [3], severe wind events presents a growing challenge to transportation resilience worldwide.

Downbursts are intense, localised wind phenomena generated by convective downdrafts within thunderstorms, producing sudden radial outflows that can reach extreme velocities and exhibit highly non-stationary behaviour [4-5]. Far from being rare anomalies, they are recurrent across Europe, where climatological studies report between 20 and 40 thunderstorm days annually in many mid-latitude countries, with convectively active regions such as the Alpine foothills and Mediterranean basins experiencing over 50 thunderstorm days per year. Within this European wind climate, dominated by extra-tropical cyclones and thunderstorms [6], downbursts represent a mesoscale hazard whose destructive potential has been extensively documented in structural engineering. Their capacity to generate wind speeds exceeding 60 m/s underscores not only their role in severe damage to the built environment but also their critical impact on vehicle stability and safety, making them a central concern in transport resilience and wind engineering research.

The increasing frequency and intensity of windstorms may significantly influence road safety. The strong cross winds generated during downbursts, exacerbate aerodynamics loads compromising vehicle stability. Research in fact, has demonstrated a strong correlation between severe storm conditions and sudden changes in winds, with the occurrence of accidents. Baker and Reynolds [7] analysed data of incidents occurred under storm conditions (wind gusts over 20 m/s) highlighting that their incidence in vehicle incidents is significantly higher than what registered in standard weather conditions. Some researchers have investigated the stability of road vehicles under generic crosswind conditions, demonstrating that sufficiently strong wind speeds may result in serious incidents, including overturning, excessive yaw rotation, or pronounced deviations from the intended trajectory [8-11].

Existing standards for assessing stability of road vehicles under crosswind conditions are present in the ISO standards [12]. This standardised test primarily consider uniform wind profiles derived from generic synoptic-scale winds, and do not consider the effect of the driver. However, these standards do not account for more dynamic and potentially hazardous conditions such as thunderstorms. In a recent study [13] a comparative analysis between a deterministic uniform wind gust model and a stochastic turbulent wind time history was proposed. The findings indicate that disregarding turbulence can result in a significant underestimation of accident risk.

In recent years, research into vehicle stability under transient wind conditions using numerical simulations has gained considerable attention and is increasingly regarded as a valuable tool for analysing wind effects on vehicle behaviour. However, no standardised methodology has yet been established, and a wide range of approaches have been employed [14-16]. In this line, the study presented in [17] conducts a comparative assessment across three types of equivalent wind profiles, three approaches for estimating aerodynamic forces, and three vehicle dynamics models. This analysis underscores the diversity of methodologies in current practice and reveals the absence of a unified framework or widely applied methodology for evaluating vehicle stability in wind-exposed conditions.

One of the most concerning aspects when modelling the behaviour of road vehicles regards the impacts of the driver. In this matter, most of the studies model the vehicle–driver system, excluding the driver. Which is aligned with the ISO standard approach in which the steering wheel is held fixed. Some authors, including those in [14] and [15], have incorporated basic driver behaviour models using simple control algorithms. Nonetheless, there is broad agreement across the literature that the absence of a driver model, constitutes a significant simplification of the vehicle-driver interaction. More recent studies have also explored the use of driving simulators to account for driver behaviour [16-22]. In a preliminary investigation into vehicle response under crosswind conditions using a driving simulator [16], the authors demonstrated that variations in wind-induced vehicle behaviour were clearly perceived by the test drivers, thereby confirming the potential of driving simulators for studying stability in crosswind scenarios. Furthermore, in [22], research conducted using both a Multi-Body vehicle model without a driver and a driving simulator revealed that driver perception of safety has a significant influence on the results.

Moreover, although certain models have been applied to the study of transient crosswind scenarios, such as tunnel exits, bridge pylon crossings, and similar situations, there remains a notable lack of research addressing the behaviour of road vehicles under full windstorm conditions.

With the intention to address this gap is born the CROSS-STORM project [23-25], a study aimed at developing a risk map that classifies thunderstorm-related scenarios and parameters into defined levels of accident risk, with particular attention to non-synoptic wind conditions. This project is divided into three main stages: the development of a wind model that accurately simulates the wind velocity field experienced by vehicles during a thunderstorm downburst [26, 27], calculating the aerodynamic loads acting on the vehicle, and evaluating the dynamic response of the vehicle-driver system.

2 Simulation model

This section presents the modelling framework adopted to investigate the interaction between road vehicles and downburst wind phenomena. It is structured into three main parts: Section 2.1 describes the vehicle model developed in VI-CarRealTime, detailing its multibody architecture and the integration of key subsystems such as suspension, steering, and tyre dynamics. Section 2.2 introduces the driver model implemented in Simulink, with reference to experimental tests conducted in the dynamic Driving Simulator of Politecnico di Milano to capture realistic driver responses under storm wind conditions. Section 2.3 focuses on the aerodynamic loads acting on the vehicle, beginning with the characterisation of the downburst wind field (Section 2.4), followed by the experimental determination of aerodynamic coefficients for the modelled vehicle (Section 2.5). Together, these components form the basis for simulating the coupled vehicle-driver system under transient and highly unsteady aerodynamic disturbances.

2.1 Vehicle model

The vehicle model adopted for the simulations is implemented in VI-CarRealTime, a simulation platform developed by VI-Grade. This environment provides a real-time multibody simulation framework that balances computational speed with modelling accuracy. It also supports co-simulation with MATLAB Simulink, allowing for seamless integration with driver controller module systems and aerodynamic loads calculation module.

The vehicle is represented by a multibody model with fourteen degrees of freedom (DOF), as illustrated in Fig. 1. It consists of five rigid components: the chassis (sprung mass) and four wheels (unsprung masses). Of the fourteen DOFs, six are associated with the vehicle body, comprising three translational motions along the longitudinal, lateral, and vertical axes, and three rotational motions about these axes. The remaining eight DOFs correspond to the wheels, capturing the vertical displacement and rotational spin of each individual tyre.

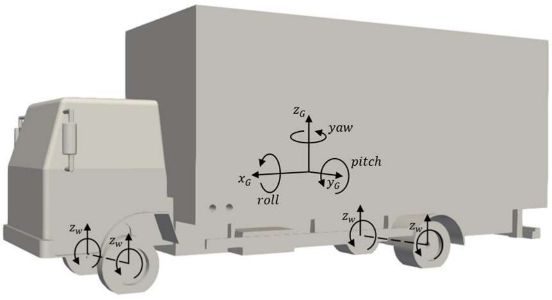

Fig. 1. Scheme of the 14 DOF multibody model of the small lorry.

The model incorporates parametric representations of subsystems, including the suspension, steering system and powertrain. Tyre-road interaction is modelled using the Pacejka Magic Formula [28]. This model enabled a fast yet accurate representation of vehicle behaviour, making it suitable for real-time simulation applications. As a result, the exact same model could be employed both in off-line simulations incorporating the driver controller and in driving simulator experiments with the driver-in-the-loop.

The vehicle model considered in this paper corresponds to a high-sided small lorry. The most relevant parameters of the vehicle model are described in Table 1, where all spatial references are made with respect to the location of the front axle.

Table 1. Main characteristics of the empty small-lorry vehicle.

Parameter	Value
Wheelbase	4450 mm
Longitudinal CG Distance	1817.1 mm
Lateral CG Distance	0 mm
Vertical CG Distance	1183.6 mm
Total Mass	5361 kg
Sprung Mass	3911 kg
Roll Moment of Inertia	1.837×10^{9} mm^{4}
Pitch Moment of Inertia	1.196×10^{10} mm^{4}
Yaw Moment of Inertia	7.158×10^{9} mm^{4}

2.2 Driver model

A driver model implemented in Simulink is used to simulate driver behaviour within the vehicle simulation framework. The model corresponds to a path-following controller that adjusts the steering wheel angle to minimise both lateral distance error and heading error. A graphical representation is presented in Fig. 2. The distance error is defined as the lateral deviation between the centre of gravity, evaluated at a preview distance, and the centre line of the lane. The heading error corresponds to the angular deviation between the vehicle orientation and the predefined trajectory.

At each simulation time step, the controller module receives several input variables from VI-CarRealTime: side-slip angle, longitudinal velocity, longitudinal acceleration, yaw angle, and the coordinates of the centre of gravity (x_G, y_G). The model also requires the coordinates of the centre line of the lane to compute the reference path. Based on this data, heading and distance errors are calculated. The steering angle is then determined as the combination of a proportional controller for the heading error and a proportional-integral controller for the distance error. The parameters of the controller were tunned using the results from an experimental campaign performed in the Politecnico di Milano Driving Simulator with 40 test drivers.

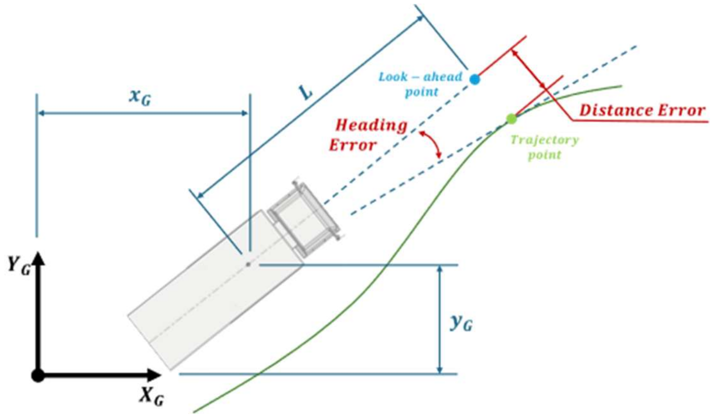

Fig. 2. Scheme of the path follower controller.

2.3 Aerodynamic loads

Aerodynamic loads acting on the vehicle are computed using a quasi-static approach. In this method, aerodynamic forces and moments are evaluated at each simulation time step based on the instantaneous vehicle state, without accounting for transient aerodynamic effects. The calculation relies on the relative velocity between the vehicle and the surrounding airflow, which is determined from the vehicle velocity and orientation provided by VI-CarRealTime, and the wind velocity extracted from the downburst wind field. Aerodynamic coefficients, obtained from wind tunnel measurements, are applied to compute the resulting forces and moments. Each aerodynamics force component, F_i, and moment component M_i, is computed according to equation 1 and 2, respectively, where ρ is the air density, A_{ref} is the reference area, L_{ref} is the reference length, $\left(\beta_{rel}(t)\right)$ is the aerodynamic coefficients which depends on the angle of the attack at time t, and $v_{rel}(t)$ is the relative velocity at time t.

$$F_i = \frac{1}{2}\rho A_{ref} C_i\left(\beta_{rel}(t)\right) v_{rel}^2(t) \tag{1}$$

$$M_i = \frac{1}{2}\rho A_{ref} L_{ref} C_i\left(\beta_{rel}(t)\right) v_{rel}^2(t) \tag{2}$$

2.4 Downburst wind field

The European wind climate is characterised by the coexistence of large-scale extra-tropical cyclones and mesoscale thunderstorms. Unlike cyclones, thunderstorms produce intense, localised downdrafts known as downbursts which, upon reaching the ground, spread radially and generate high-velocity wind fields that differ markedly from synoptic-scale flows.

These outflows exhibit non-stationary behaviour, with a “nose profile” that produces severe wind velocities close to the surface [29,30]. To capture this, Xhelaj et. al [24] proposed an analytical model reconstructing the two-dimensional wind field of downbursts, in which horizontal wind speed is expressed as the vector summation of the impinging jet, the downdraft translation, and the background wind field [31]. The model reproduces the space-time evolution of mean wind speed and direction, with parameters linked to meteorological variables statistically assessed in projects such as European THUNDERR [32]. The approach adopted in this work builds upon the methodology presented in [24] and provides a fast and reliable procedure for simulating the wind velocity field produced by a downburst as experienced by a vehicle travelling through it.

The model follows a four-step process. First, the horizontal, slowly varying mean wind velocity field of a travelling downburst at a generic height above ground level is modelled using established techniques [26]. Second, the turbulence field of the downburst is simulated as a non-stationary, non-Gaussian, bivariate, three-dimensional, partially coherent random process, using the spectral representation method [33]. The statistical properties of this process are characterised based on a comprehensive database of downburst outflows obtained through anemometric and lidar measurements. Finally, the turbulent wind field was reconstructed by superimposing the turbulence components onto the slowly varying mean wind field obtained in the previous steps. An example of the wind field of the downburst for given time is presented in Fig. 3.

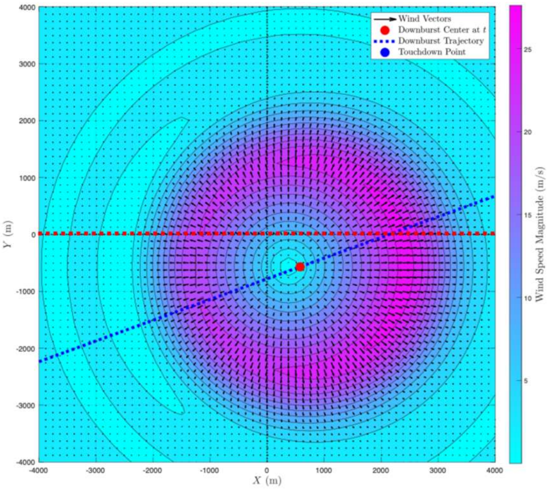

Fig. 3. Wind field corresponding to a moving downburst.

2.5 Aerodynamic coefficients

Aerodynamic coefficients were obtained through a wind tunnel testing campaign conducted in the low-turbulence test section of the Politecnico di Milano Wind Tunnel. The experiments were performed using a 1:8 scale model of the vehicle positioned in a flat ground scenario, with a uniform wind speed set to 50 m/s. The reference area used for the analysis was A_{ref} = 5 m², and the reference length was L_{ref} = 2.5 m. Under these conditions, the resulting Reynolds number was approximately 1.04×10^6, ensuring aerodynamic similarity with full-scale conditions. The results of the wind tunnel campaign are presented in Fig. 4, where the aerodynamic coefficients corresponding to all load components are shown as functions of the yaw angle.

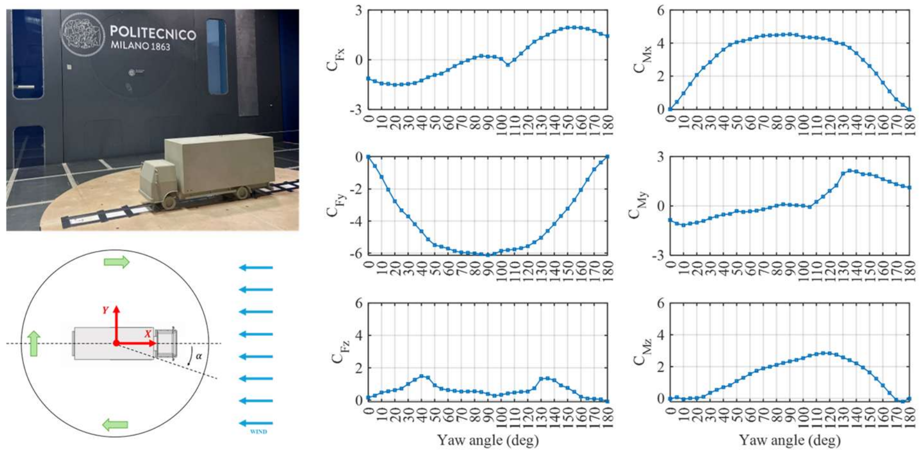

Fig. 4. Wind tunnel tests. Wind speed = 50 m/s. Model scale =1:8. a) Small lorry during wind tunnel test; b) reference system; c) aerodynamic coefficients.

2.6 Metrics

To assess the safety of the vehicle when exposed to downburst winds, two metrics were employed. The first is Lane Deviation (LD), which measures the lateral displacement from the ideal trajectory that the vehicle is expected to follow (equation (3)). Larger values of LD indicate greater deviation from the intended path, reflecting reduced lateral stability. The second metric is the Normalised Load Transfer (NLT), which quantifies the proportion of vertical load that shifts from one side of the vehicle to the other due to lateral aerodynamic forces (equation (4)). Values further from zero indicate more significant load transfer. A negative value corresponds to unloading on the left side of the vehicle, while a positive value indicates unloading on the right side. These metrics provide insight into both trajectory control and load distribution, which are critical for evaluating the risk of lane departure and rollover.

$$LD = \sqrt{\left(x_G - x_{ref}\right)^2 + \left(y_G - y_{ref}\right)^2} \tag{3}$$

$$NLT = \frac{F_{z,L} - F_{z,R}}{F_{z,L\_st} + F_{z,R\_st}} \tag{4}$$

3 Results

In this section the results of the simulation aimed at evaluating the dynamic response of the small lorry subjected to a downburst wind event are presented. The scenario considered involved an unladen small lorry travelling at a constant speed of 80 km/h along a straight trajectory (coincident with x axis in Fig. 3) while crossing the moving downburst. The results of the simulation, in terms of Lane Deviation, and Normalised Load Transfer, are shown in Fig. 5.

The results revealed that the Lane Deviation shows values greater than 1 m, that considering the vehicle dimensions, indicates that the vehicle crossed into the adjacent lane, representing a serious safety risk, particularly in multi-lane traffic conditions. Additionally, the Normalized Load Transfer Index showed that, at certain instants, one of the rear wheels experienced complete unloading, suggesting a potential loss of contact with the road surface. This condition is especially hazardous, as it may lead to loss of control or even rollover. These findings emphasised the vulnerability of high-sided vehicles when exposed to intense lateral aerodynamic loads and demonstrated the critical nature of downburst encounters in terms of vehicle stability and accident risk.

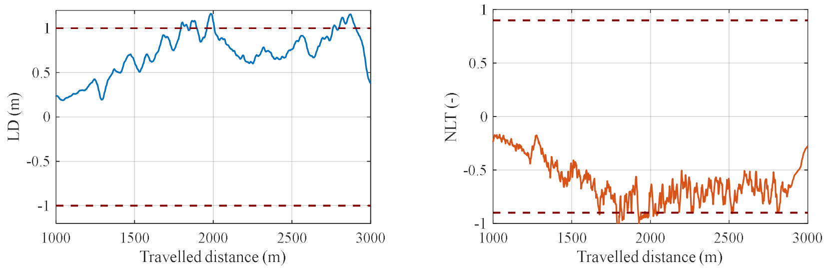

Fig. 5. Simulation results of a small lorry at 80 km/h, straight road in terms of Lane deviation (LD) and Normalised Load Transfer (NLT).

4 Conclusions

In this work a comprehensive methodology to assess the stability of road vehicles under extreme downburst wind conditions has been developed. The approach included the simulation of the downburst wind field, from which the time history of the wind velocity experienced by the vehicle was obtained. This information was used within the vehicle simulation framework to compute aerodynamic loads at each time step, based on vehicle position and orientation, following a quasi-static formulation.

The study focused on a high-sided small lorry, modelled using a 14-degree-of-freedom multibody representation developed in VI-CarRealTime. Aerodynamic characterisation was carried out through wind tunnel testing, which provided the aerodynamic coefficients required for the simulation. A driver model was implemented and validated through an experimental campaign conducted in the driving simulator.

The results demonstrated that a high-sided lorry represents a serious safety risk when exposed to the intense and rapidly varying winds generated during a downburst event.

These efforts contributed to a deeper understanding of vehicle behaviour in severe weather conditions and supported future developments aimed at improving road safety and resilience.

Acknowledgements

The project CROSS-STORM has been funded by EU, NextGenerationEU, M4C2I1.1, Project PRIN 2022 PNRR “CROSS-STORM”, Prot. 202284ZER9 – CUP D53D23003170006

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