Analysis of vehicle dynamics under sadden cross wind

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Abstract. In this paper, the way of calculating aerodynamic forces acting on a vehicle passing in the region of sadden cross wind was presented. The CarDyn, a vehicle dynamics simulation program, developed by the author was used. The effects of the cross wind were studied with a fixed steering wheel simulation. On the base of computer simulations the car cross wind sensitivity were determined, and vehicle responses such as lateral offset, side acceleration and yaw angular velocity are presented.

1. Introduction

During the drive, car vehicles are particularly exposed to a series of dangerous situations. Those situations may result from the technical condition of the vehicle, the driver extortion and the weather conditions. One of such a dangerous situation, resulting from the weather conditions, can be impact of crosswind on vehicle.

Road test results and computational fluid dynamics numerical simulations (CFD) show that crosswind-vehicle interaction affects both the frontal aerodynamic drag, as well as lateral drag and the aerodynamic lift force.

However, in a fundamental way, the crosswind cause occurrence of the significant component of aerodynamic reaction on lateral axis direction and yawing moment around vertical axis of vehicle. The last one results from the fact that centre of wind pressure of coachwork is situated usually out of the vehicle centre of mass. Influence of crosswind on the vehicle motion can have a significant impact in case of a vehicle driving into open area, e.g. from forested area or during a overtaking maneuver of truck tractor with trailer. Experimental tests of the car vehicle behaviour under the crosswinds impact are performed in aerodynamic tunnel [4], or during road tests with the use of a wind generator, in accordance with ISO 12021 standard [8]. Road tests should be carried out on dry, paved roads with optimal case of asphalt surface. In special cases, test are allowed to be performed on wet surface, providing the measurement of the water layer depth on the pavement. The preferred length of the wind zone during the test is equal to 25 meters. The velocity of the natural wind during the experimental procedure should be minimized and should not exceed 3 m/s in each direction. The wind generator should produce wind with its velocity equal to 20 ±3 m/s. The direction of generated wind should be perpendicular to the direction of the car vehicle motion. The researchers are conducted for cars, cars with trailers and light truck. Another possibility of the influence of crosswind on car vehicle is conducting the computer numerical simulations using a methods of the Computational Fluid Dynamics (CFD) [3].
2. Mathematical model of vehicle

The vehicle, in the author's program CarDyn, is modelled as a system of rigid bodies described by state parameters, which are divided into two groups: generalized coordinates (y) and generalized velocities (z). In order to describe the motion of rigid bodies with respect to the car body configuration coordinates are chosen, to give a the minimum number of differential equations of motion, since some of these degrees of freedom are eliminated through geometric constraints.

Differential equations of motion have been divided into two groups, the kinematic equations and the dynamic equations. The kinematic equations are expressed by the relationship between generalized coordinates and generalized velocities. The form of these equations depends on the choice of the generalized coordinates and the generalized velocities.

In general case, the kinematic equations have the form:

\[ \frac{d}{dt} [y] = K^{-1} [z] \] (1)

where \( K \) – kinematic matrix.

The dynamic equations take the form:

\[ M_{pq} \ddot{z}_p = Q_p \] (2)

General form of symmetric mass matrix \( M_{pq} \) and generalized forces vector \( Q_p \) take following form:

\[
M_{pq} = \sum_{i=1}^{\frac{k}{2}} \left\{ \frac{\partial \mathbf{v}^T_{O_i, N}}{\partial z_p} m_i \frac{\partial \mathbf{v}_{O_i, N}}{\partial z_q} + \frac{\partial \mathbf{\omega}^T_{O_i, N}}{\partial z_p} T_{S_i, N} \frac{\partial \mathbf{\omega}_{O_i, N}}{\partial z_q} \right\} \times \mathbf{f} (3)
\]

\[
Q_p = \sum_{i=1}^{\frac{k}{2}} \left\{ \frac{\partial \mathbf{v}^T_{O_i, N}}{\partial z_p} \left[ F_{i, N} - m_i a^R_{O_i, N} \right] + \frac{\partial \mathbf{\omega}^T_{O_i, N}}{\partial z_p} \left[ M_{i, N} + T_{S_i, N} \mathbf{\omega}^R_{O_i, N} - \omega_{O_i, N} \times T_{S_i, N} \mathbf{\omega}_{O_i, N} \right] \right\} \times \mathbf{f} (4)
\]

where:

\( m_i \) – the mass the \( i \)th body,

\( T_{S_i, N} \) – the inertia tensor of the \( i \)th body with respect to the vehicle-fixed reference frame \{N\},

\( F_{i, N} \) and \( M_{i, N} \) – external forces and moments,

\( a^R_{O_i, N} \), \( \omega^R_{O_i, N} \) - “residual” accelerations [9] of the \( i \)th body centre of mass.

The vehicle is modelled as a system 9 rigid bodies with 17 degrees of freedom:

- vehicle body – 6 degrees of freedom,
- front suspension – 5 degrees of freedom,
- rear suspension – 2 degrees of freedom,
- each of the wheels – 1 degree of freedom.

The simulation program adopted nonlinear characteristics of elastic-damping elements of suspensions, designated on the basis of experimental research.

In order to describe the interaction of wheel tires with the road surface, the TM-Easy tires model [9] is used, modified in papers [11], [12]. The model takes into account the elastic-damping properties of tires in vertical, longitudinal and transverse direction.

The transient states of each tire are described in two differential equations of the first order [9], [12].
3. Aerodynamic forces and moments acting on the vehicle

Taking advantage of mentioned in research methods, one can assign aerodynamic forces and moments acting on vehicle for given car motion condition and wind velocity and direction. If car vehicle in driving with velocity $\mathbf{v}_{0,0}$, whereas air is moving with velocity $\mathbf{v}_{w,0}$, then the velocity of relative motion of moving air to vehicle is equal to:

$$\mathbf{v}_{w,0} = \mathbf{v}_{w,0} - \mathbf{v}_{0,0}$$  (1)

In the system of vehicle body, this velocity is equal to:

$$\mathbf{v}_{r,N} = \mathbf{A}_{ON}^T \cdot \mathbf{v}_{w,0}$$  (2)

where:

$\mathbf{A}_{ON}$ – the matrix of the transformation from the system associated with the body to the absolute system,

$\psi$ – the yaw angle,

$\theta$ – the pitch angle,

$\phi$ – the roll angle.

$$\mathbf{A}_{ON} = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{bmatrix}$$

While the length of the velocity vector is equal to:

$$v_r = |\mathbf{v}_{r,N}| = \sqrt{v_{r,N,x}^2 + v_{r,N,y}^2 + v_{r,N,z}^2}$$  (3)

In case analysed plane motion, the velocity of the relative motion of air and vehicle, and the angle of deviation of relative velocity from the longitudinal axis of the vehicle may be expressed in following relationship:

$$v_r^2 = (v_N + v_w \cos \psi)^2 + v_w^2 \sin^2 \psi$$

$$\beta = \frac{v_w \sin \psi}{v_N + v_w \cos \psi}$$  (4)
Aerodynamic forces and moments acting of the vehicle, which are a consequence of cross-interaction of car and air, are the resultant of normal surface forces which come from pressure distribution on car surface and tangential forces which are a consequence of air viscosity. This are viscosity causes a complex flow around the vehicle, thus the assignation of the aerodynamic forces and moments is conducted by the use of empirical dependences:

\[
F_{\text{Air}} = \begin{bmatrix} F_{\text{Air},x} \\ F_{\text{Air},y} \\ F_{\text{Air},z} \end{bmatrix} = A \cdot \frac{\rho}{\rho_0} \cdot \frac{v^2}{2} \begin{bmatrix} c_{Fx} \\ c_{Fy} \\ c_{Fz} \end{bmatrix}
\]

\[
M_{\text{Air}} = \begin{bmatrix} M_{\text{Air},x} \\ M_{\text{Air},y} \\ M_{\text{Air},z} \end{bmatrix} = A \cdot L_O \cdot \frac{\rho}{\rho_0} \cdot \frac{v^2}{2} \begin{bmatrix} c_{Mx} \\ c_{My} \\ c_{Mz} \end{bmatrix}
\]

where:
- \( A \) – the frontal area,
- \( \rho \) – the air density,
- \( \rho_0 \) – the air density,
- \( L_O \) – the vehicle wheel base,
- \( c_{Fx}, c_{Fy}, c_{Fz}, c_{Mx}, c_{My}, c_{Mz} \) – dimensionless coefficients of the drag force, the lateral force, the lift force, the pitching moment, the rolling moment and the yawing moment.

A typical characteristics of the aerodynamic dimensionless coefficients for a car vehicle [1] are presented in figure 2.

Figure 2. Typical characteristics of the aerodynamic dimensionless coefficients for a passenger car according to [1].

As it follows from the presented characteristics, during the symmetrical flow around the vehicle (\( \psi = 0 \)), a car is only under the load of the drag force (\( F_{\text{Air},x} \)) and the lift force (\( F_{\text{Air},z} \)). The stability and the steerability of the car and the road safety under the cross wind is under the greatest influence of the lateral force (\( F_{\text{Air},y} \)) and the yawing moment (\( M_{\text{Air},z} \)). Due to this fact, in the simulation program, following aerodynamic forces and moments are included:
- the drag force (\( F_{\text{Air},x} \)),
- the lateral force (\( F_{\text{Air},y} \)),
- the yawing moment (\( M_{\text{Air},z} \)).
The lateral force is acting on the car body in point called the centre of pressure (COP), which usually is not coincident with the centre of mass of the vehicle. Due to this fact, during the car drive through the area of cross wind, the yawing moment acting on the car is produced, thus it leads to the change of the drive direction.

Location of the centre of pressure (COP) with respect to the centre of mass which is used to assign aerodynamic moments acting on the vehicle can be determined by the comparison of dependence describing the lateral force multiplied by the arm of its action with the relationship of the yawing moment. It leads to formula:

$$r_{Air,x} = \frac{C_{Mz}}{C_y} \cdot L_o$$  \hspace{1cm} (6)

$$F_{Air,y} = \frac{A_y(x)}{A_{y0}} A \cdot \frac{\rho \cdot V^2}{2} \cdot c_{Fy}$$  \hspace{1cm} (7)

where:

- $A_y$ – the lateral area,
- $A_y(x)$ – lateral surface of the car body directly exposed to the wind (fig. 4-5),
For this reason, the lateral surface of the car has been divide into section, thereby defining the relationship describing the lateral surface of the car directly exposed to the cross wind. It is assumed, that the yawing moment is caused by the aerodynamic lateral force applied at the point called the centre of pressures and it is also proportional to car lateral surface which is directly exposed to the cross wind.

\[
A_y = -0.0669x^3 + 0.4228x^2 + 0.3512x
\]

\[A_y = 0.0525x^2 - 0.3732x^2 - 0.3505x + 3.3161\]

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Figure 4. The lateral surface of the car body directly exposed to the wind a) in the stage when car is driving in a cross wind area, b) in the stage when car is driving out of this a cross wind area.

Figure 5. The relationship describing the lateral surface of the car directly exposed to the wind: a) in the stage of driving in the cross wind area in the function of the distance of the front of the car to the starting point of the wind area, b) in the stage of driving out of the cross wind area in the function of the distance of the front of the car to the ending point of the wind area.

Relationships describing aerodynamic coefficients used in this research are developed on the basis of the formula given in paper [2] and characteristics of dimensionless aerodynamic coefficients for a small car, illustrated in figure 2, taken from [7]. Aerodynamic coefficients used in the simulation are determined from the following relationships:

\[
c_{Fz} = 0.33 \cdot (1 + \sin(3\beta))
\]

\[c_{Fy} = 2.48 \cdot \beta^{0.382}\]

\[c_{Mz} = 2 \cdot \beta^{1.77}\]
4. Simulation tests
In the analysis, a small car is chosen with the wheel base equal to 2.2 m and total mass equal to 940 kg. Simulation research have been carried out for three different driving speeds corresponding to the maximum speed limits for different type of roads – 50 km/h, 90 km/h and 140 km/h respectively. In the simulation the kinematic input coming from unevenness of the road surface is omitted. Simulations have been performed with the steering wheel hold down in toward direction. It is assumed that the car is driving through the 20 m long area of cross wind which flows with three different velocities equal to 20 m/s, 25 m/s and 30 m/s respectively (see in figure 6).

![Figure 6. The geometry of driving maneuver in cross wind area according to [7]](image)

Results of selected simulations are presented in graphs (figures 7-9). Results present the lateral displacement of the car in function of time. Safety of driving car is dependent on this parameter. The maximum allowable lateral displacement is assumed as a distance equal to 1 m at time of 1 s form the driving the car in the cross wind area. Adopted time is equal to the time of psychophysical response of the driver to identified abnormal behaviour of the car. Allowable displacement results from the average width of the car equal to 1.5 m, which driving around the lane axis of its width equal to 3.5 m, has approximately 1m distance to the lane border [5].

![Figure 7. Driving of the small car with speed of 50 km/h through the cross wind area blowing with velocity equal to 20 m/s, 25 m/s and 30 m/s a) lateral displacement of the vehicle, b) yaw velocity.](image)
5. Summary

Presented simulation results indicates that for adopted date relating to the aerodynamic coefficients, driving the analysed car with speed of 50 km/h through the cross wind area, the safety criterion is satisfied for the cross wind blowing at speed of approximately 30 m/s. For the driving with speed of 90 km/h through the cross wind area, the safety criterion is satisfied for the cross wind blowing at speed of approximately 20 m/s, whereas for a driving speed of 140 km/h the safety criterion is satisfied for neither of analysed wind speed.

The developed mathematical model of the car, implemented in the author's program CarDyn gives wide opportunity to test the behaviour of car vehicles exposed to the cross wind action. It can be useful in reconstruction of road accidents, for which the sudden change of trajectory of the car motion could be caused by the drive through the area of cross wind, which can take place on bridges, viaducts, during driving out of the forested areas, or during overtaking large trucks.

Verification of adopted aerodynamic dimensionless coefficients for the analysed car is planned through the numerical simulation of air flow around a vehicle with the use of Computational Fluid Dynamics method (CFD).
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