

Analysis of Vehicle Lateral Dynamics due to Variable Wind Gusts

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ABSTRACT

This study presents a practical theoretical method to judge the aerodynamic response of buses in the early design stage based on both aerodynamic and design parameters. A constant longitudinal velocity 2-DOF vehicle lateral dynamics model is used to investigate the lateral response of a bus under nine different wind gusts excitations. An appropriate 3-D CFD simulation model of the bus shape results is integrated with carefully chosen design parameters data of a real bus chassis and body to obtain vehicle lateral dynamic response to the prescribed excitations.

Vehicle model validity is carried out then, the 2-DOF vehicle lateral dynamics model has been executed in MATLAB Simulink environment with the selected data. Simulation represents the vehicle in a straight ahead path then entered a gusting wind section of the track with a fixed steering wheel. Vehicle response includes lateral deviation (LD), lateral acceleration (LA), yaw angle (YA) and yaw rate (YR). Results showed that in case of 25 m/s wind gust [which corresponds to 45° wind relative yaw angle (β_w)], the vehicle Lateral Deviation (LD) maintained about 5 m after 4.5 seconds of entering the wind gust. Moreover, vehicle Yaw Rate (YR) reaches a maximum value of about 2.3deg/s during such maneuver simulation time.

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1. INTRODUCTION

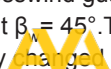
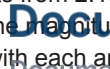
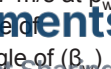
When driving a vehicle on the road, the driver has to compensate continuously for small directional deviations from the desired course due to disturbances such as crosswinds and road irregularities leading to unintended path deviation. With higher and larger side area such as buses and trucks, the influence of crosswind on the vehicle lateral dynamics behavior is much higher and the vehicle becomes more sensitive to side wind excitations.

In a real case for such non-steady motion of a vehicle, the aerodynamic loads influence its directional stability and overall safety. Prototype vehicles have been used to check vehicle stability by actual driving tests to evaluate the effect of transient aerodynamics. However at this stage it is often too late to make changes to neither vehicle shape nor vehicle chassis design parameters [1]. In order to reduce the cost of developing a new vehicle and allow early intervention, much research activity has involved developing handling and stability simulations to study the effect of aerodynamics during the early design phase. The aerodynamic models used in such simulations are determined from experimental quasi-steady wind tunnel tests performed on full scale vehicle shape model, or on a scaled one [1].

However the essential crucial way to judge the crosswind stability of a vehicle is through experiments, numerical simulations are more flexible to set up and design compared to experiments [2]. In the last decade, many researchers have investigated the aerodynamic characteristics of ground vehicles using CFD techniques [3,4,5] and they concluded that CFD is a strong tool to assess ground vehicle aerodynamics in primary design stages. The present work goal is to introduce a proper integration between CFD results for 3-D bus shape model and the mathematical model that represents vehicle lateral dynamics. The main lateral dynamics parameters of a vehicle that have an impact on its response are reported in details.

2. CFD SIMULATION METHODOLOGY

2.1. Bus Model Simulation Objectives

In order to determine the aerodynamic characteristics (which is essential for the mathematical modeling); a 3-D CFD simulation of bus model has performed using the industrial software ANSYS-Fluent 14.0 [6]. The numerical simulation strategy is to impose a resultant wind velocity (V_w) with variable magnitudes and directions of wind relative yaw angle (β_w) to simulate the variation in crosswind gusts from 2.187 m/s at $\beta_w = 5^\circ$ to 25 m/s wind velocity at $\beta_w = 45^\circ$. The magnitude of crosswind gusts is relatively     with each angle of (β_w)

according to the value of resultant wind velocity lateral component ($V_w \sin \beta_w$) (which represents lateral wind gust velocity (V_l)) as shown in (Figure 1). The studied range is from $\beta_w = 5^\circ$ to $\beta_w = 45^\circ$ with step 5° . That has been applied to the 3-D bus model with constant upwind speed 25 m/s.

All the details of CFD simulation (bus model design, grid independence study, turbulence model investigation and selection, computational domain dimensions and shape, final grid settings, obtained velocity contours, and surface pressure distribution) are presented by William, Y.E. *et al* [7]. The major CFD parameters are mentioned in (Table 1).

Table 1. Major CFD parameters.

Turbulence Model	Realizable k- ϵ
Discretization Scheme	Second-order upwind scheme for all variables
Solving Algorithm	Semi-implicit method for pressure linked equation (SIMPLE)
Number of Elements	10.9 Million (approximately)
Maximum Residual for All Parameters	10^{-4}

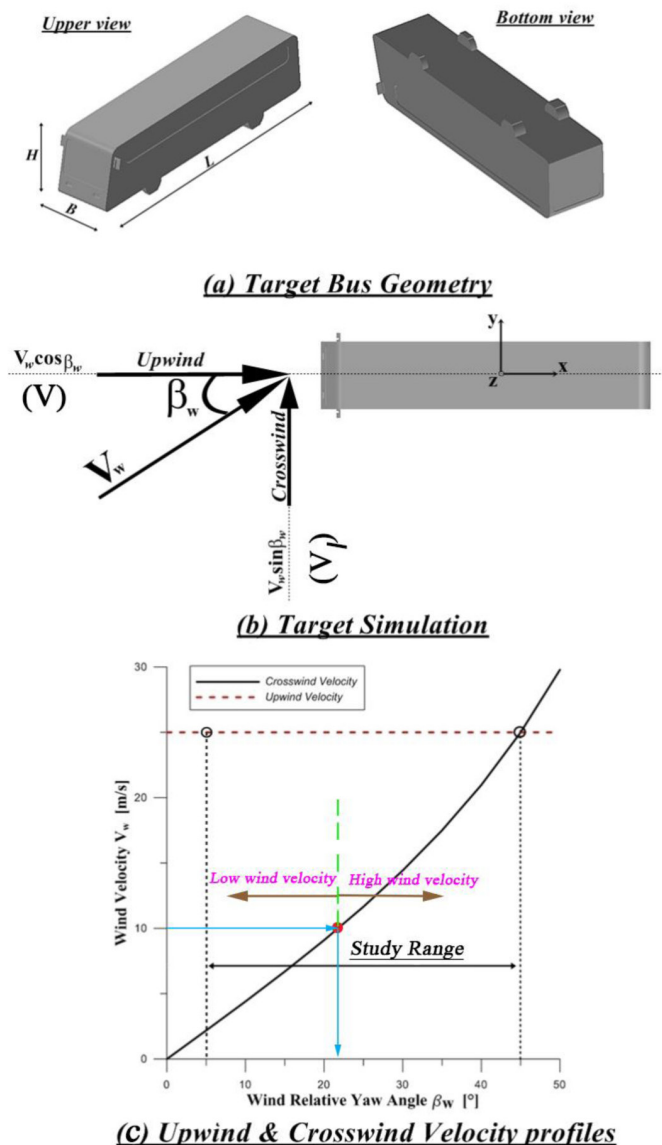


Figure 1. Overview of target bus geometry and simulation strategy.

2.2. CFD Obtained Results

However the six aerodynamic components are reported from the CFD simulation, only side force (F_s) and its aerodynamic center (AC) position are required to perform the 2-DOF vehicle lateral dynamics mathematical modeling simulation. Side force (F_s) parameters which are demonstrated in Eq.(1&2) are important to understand the produced side force (F_s) from each wind gust. From five influencing parameters on the value of wind gust side force (F_s), only two are changing during CFD simulation (which are side force Coefficient (C_s) and lateral wind gust velocity (V_l)).

$$F_s = 0.5 * \rho_{air} * A_f * C_s * V_w^2 \quad (1)$$

And (V_w) can be expressed as:

$$V_w^2 = V^2 + V_l^2 \quad (2)$$

Each wind gust has a specific three characteristics (which are side force Coefficient (C_s), lateral wind gust velocity (V_l), and distance between vehicle aerodynamic center (AC) and its rear end (L_w). However, the side force coefficient (C_s) is directly proportional with lateral wind gust velocity (V_l), the aerodynamic center distance (L_w) has another behavior. With increasing of wind relative yaw angle (β_w)(which corresponds lateral wind gust velocity(V_l), a huge pressure difference is generated between bus model two side surfaces.

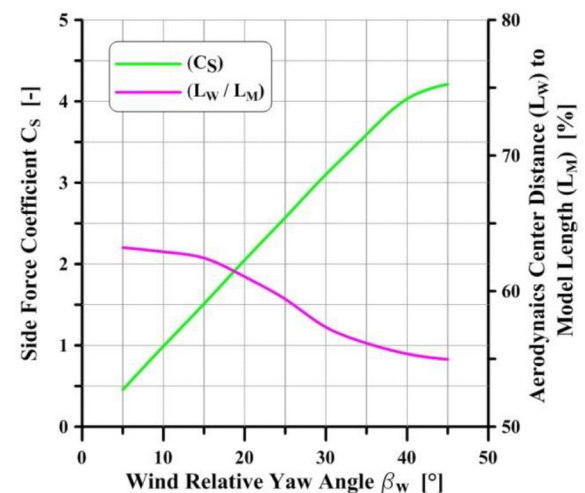


Figure 2. Variation of side force coefficient and aerodynamic center distance with (β_w).

Side force coefficient (C_s) value is depending on this pressure difference which explains the rising tendency of the curve. The aerodynamic center (AC) position is changing according to the change in pressure distribution of air on bus model all surfaces. Due to increasing in lateral wind gust velocity (V_l), the pressure stagnation area (the sum of stagnation points and lines at which the static pressure has its maximum value) of bus model side surfaces is increasing. Moreover, the position of

aerodynamic center (AC) changed by lateral wind gust is shifted to be more closer to bus model rear end as shown in (Figure 2).

3. VEHICLE LATERAL DYNAMICS MODELING

3.1. Vehicle Motion in Lateral Wind Gust

A simple 2-DOF lateral dynamics model is used to determine the vehicle lateral response due to variable wind gusts. The used model is presented by Abe, M. [8] and Hucho, W.H. [9], however, with a little modification as presented in Eq.(3&4). In order to fit the used mathematical model with bus criteria, each (K_f) is replaced by ($2K_f$) as a result of four wheels in the vehicle rear axle existence. The established model considers situation where vehicle is traveling straight ahead ($\delta=0$) with a constant velocity (V = Constant) (V also represents upwind velocity during CFD simulation in which the vehicle is assumed to be stationary and air is moving), then, subjected to a sudden lateral wind gust with velocity (V_l). A side force (F_s) is generated which acts at the vehicle AC. The distance between vehicle CG and vehicle AC is (l_w).

$$m \frac{d^2 y}{dt^2} + \frac{2(K_f + 2K_r)}{V} \frac{dy}{dt} + \frac{2(l_f K_f - 2l_r K_r)}{V} \frac{d\theta}{dt} - 2(K_f + 2K_r)\theta = F_s \quad (3)$$

$$I \frac{d^2 \theta}{dt^2} + \frac{2(l_f K_f - 2l_r K_r)}{V} \frac{dy}{dt} + \frac{2(l_f^2 K_f + 2l_r^2 K_r)}{V} \frac{d\theta}{dt} - 2(l_f K_f - 2l_r K_r)\theta = -l_w F_s \quad (4)$$

As a result of vehicle tires cornering stiffness, an internal lateral vehicle force is produced which is ($2\beta(K_f + 2K_r)$). This force is acting in the vehicle neutral steer point (NSP) as shown in (Figure 3). The distance between vehicle CG and vehicle NSP is (l_N). Both of (l_N) and (l_w) are taken as positive if the NSP and AC are behind the vehicle CG. Actually (l_N), which is shown in Eq.(5) determines the vehicle handling behavior (i.e. under/over steer). However, in such simulation the investigated vehicle response will be quite different. Regarding current simulation conditions, either clockwise (CW) or counterclockwise (CCW) settling yaw motion of vehicle CG is the main expected behavior.

$$l_N = -\frac{(l_f K_f - 2l_r K_r)}{K_f + 2K_r} \quad (5)$$

The lateral wind gust scenarios proposed to simulate the standard Volkswagen crosswind facility [9]. This (47 m) length side wind facility is assumed to affect the vehicle after half a second of entering the facility. In other words, the lateral wind gust excitation is applied after half a second from simulation start point. The wind gust profile maintained at its maximum value after (8 m) of wind gust initialization at the beginning of

wind facility. The same distance is taken to collapse wind gust from its maximum value to zero at the end of crosswind facility. The overall wind gust duration is 1.88 seconds as shown in (Figure 4) provided that vehicle longitudinal velocity, while passing this facility, is kept at 90 km/hr. In fact, the effect of crosswind on road vehicles had been studied by similar wind gust excitations as used by [1,9,10,11].

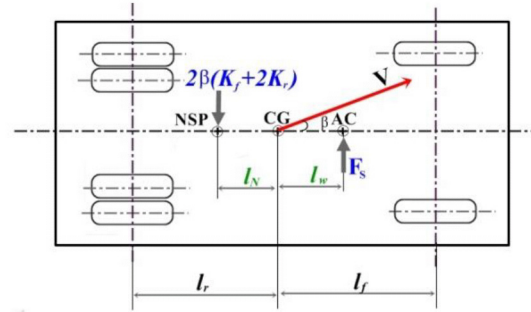


Figure 3. Bus model with existed lateral forces.

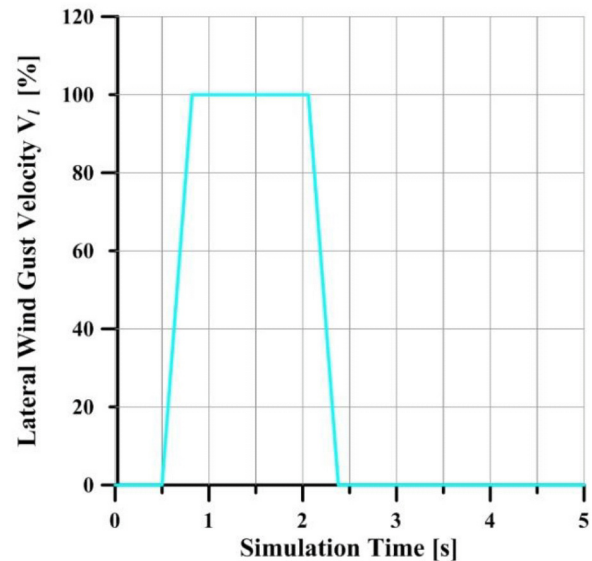


Figure 4. Lateral wind gust velocity profile.

3.2. Model Validation

Before starting in bus model lateral dynamics simulation and analysis, it was essential to judge the executed model in MATLAB Simulink [12] environment validity. A sample yaw rate (YR) response of the concluded results is compared with its parallel response reported by Abe, M. [8]. A typical vehicle chassis parameters and aerodynamic lateral wind gust excitation conditions is used. The comparison of the obtained results (Figures 5,6) has shown an identical vehicle response behavior. Which emphasizes the validity of the executed model before modifying it to be relevant with bus model simulation ($(2K_f)$ instead of (K_f)).