

University of Bahrain

College of Engineering



**Department of Mechanical
Engineering**

**Effect of High Crosswind Gust Loads on
Driver-Vehicle Handling Control**

**A Thesis submitted in Partial Fulfillment of the Requirements for the
master's degree in mechanical engineering**

Submitted by

Abdulredha Hussain Mohammed Aman

University number :19971967

Supervised By

Dr. Mustafa Habib

(Associate Professor)

University of Bahrain

Kingdom of Bahrain

April 2018

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Dissertation Deposit Form

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The Discussion Committee met on 25/4/2019 (day and date) 14-62 in Hall no. (hall/room no.) . Upon discussing the student whose details are stated above in public, the discussion committee recommends the following:

The student awarded grade A In the thesis subject Mechanical Engineering

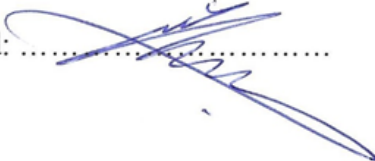
- ☐ Without making any changes to the thesis
☒ After making the modifications attached with this decision

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Declaration

I declare that this work is the result of my own investigation and it had not accepted in substance for any degree, nor it currently submitted for any degree.

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Abstract

As far as ground vehicle lateral stability is concerned, aerodynamics in gusty crosswind conditions is significant factor in the vehicle development process as well as bridge design and construction. Recent investigations have demonstrated that unsteady aerodynamic loads can exceed steady loads considerably which may decrease driving lateral stability and may lead to loss of handling control. In order to compute and evaluate the vehicle's response to crosswind gusts, it is essential to determine the aerodynamic excitation on the vehicle body. The present work is concerned with the lateral dynamic stability of ground vehicles while crossing bridges during severe, gusty crosswind conditions. In this investigation, Shaikh Isa bin Salman Bridge is considered, due to its geometrical construction properties with regard to side wind pulse generation, as an example of gusty crosswind conditions. In severe windy days, vehicles are exposed to disturbing and experiencing a pulsating crosswind while crossing the bridge. This may lead to the driver feeling that there is reduced control over the vehicle. Several accidents have been reported in local newspapers which are related to loss of lateral control in vehicle. This study focuses on the crosswind modelling of the bridge to find the variation of the aerodynamic distribution pattern at various crosswind velocities and orientations and their effect on the stability of driver-vehicle closed loop system.

Dedication

I dedicate my dissertation work to my family. Without them, this could not have been achieved.

Acknowledgment

I would like to express my deep gratitude to my thesis supervisor Dr. Mustafa Habib for his support, guidance, and encouragement in the thesis work. I would also like to thank all Mechanical Engineering Department staff for their support to complete the thesis successfully.

Very special thanks goes to Allah (s.w) who blessed me with a great family who supported and motivated me to reach where I am today.

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Nomenclature

c	Chord length of an airfoil at any point along the wing span, m
C_d	Drag Coefficient, $(D/0.5\rho V_\infty^2 A)$
C_s	Side force Coefficient, $(L/0.5\rho V_\infty^2 A)$
C_s/C_D	Side force coefficient to drag coefficient ratio
D	Drag force, N
F_s	Side force, N
P	Pressure, Pa
Re	Reynolds number, $(\rho V_\infty L/\mu)$

Greek Symbols:

α	Angle of attack, <i>degree</i>
α_{eff}	Effective angle of attack, <i>degree</i>
β	Side angle of the winglets
ρ	Density of air flow, kg/m^3

Abbreviations:

CFD	Computational Fluid Dynamics
-----	------------------------------

$y_r(t)$: Reference input.

e_y : Position error.

δ_f : Front tire actions (rad).

$y_r(t)$: Reference input.

ϕ : Vehicle yaw angle or heading angle.

$y(t)$: Vehicle lateral position.

H_S : Driver model transfer function.

$G_y(t)$: Vehicle dynamic model transfer function.

Chapter 1

Introduction to the study

Chapter One

Introduction to the study

1.1. Overview

The handling characteristics of a road vehicle refers to its response to steering commands and to environmental inputs, such as wind gust and road disturbances, that affect its direction of motion (Wong 2001).

High winds are associated with a small proportion of crashes, but generally increase the risk of traffic collisions (European Agency for Safety and Health at Work 2010). Gusts of wind can push relatively high vehicles such as busses, delivery vans, camper vans, caravans and lorries off course, and under extreme conditions, can even cause them to roll over. This happens mainly on bridges and viaducts (Institute for Road Safety Research 2012).

Shaikh Isa bin Salman Causeway in the Kingdom of Bahrain, which connects Busaiteen to the Diplomatic Area, opened to the public in January, 1997. It is easily recognized by its triangular white columns which are meant to symbolize sails. These triangular columns shown in Figure (1) may generate wind turbulence by blocking the wind which creates a nozzle effect between the columns.



Figure (1)

Triangular white columns of Shaikh Isa bin Salman Causeway (Haji Hassan ReadyMix 2012).

Formal reports or statistics about accidents due to this problem are not available; local newspapers report accidents over the bridge on different dates throughout the year. The loss control mentioned in reports may reflect different reasons; e.g. human, environmental or vehicle malfunction.

Wind velocity in the surrounding area can reach 30 m/s, as measured at Bahrain International Airport. Alnaser and Al-Karaghoul (2000), summarized the wind velocity frequency and the variation in wind direction in Figures (2) and (3). Wind velocity reaches 25 knots (over 46 km/h) in different directions.

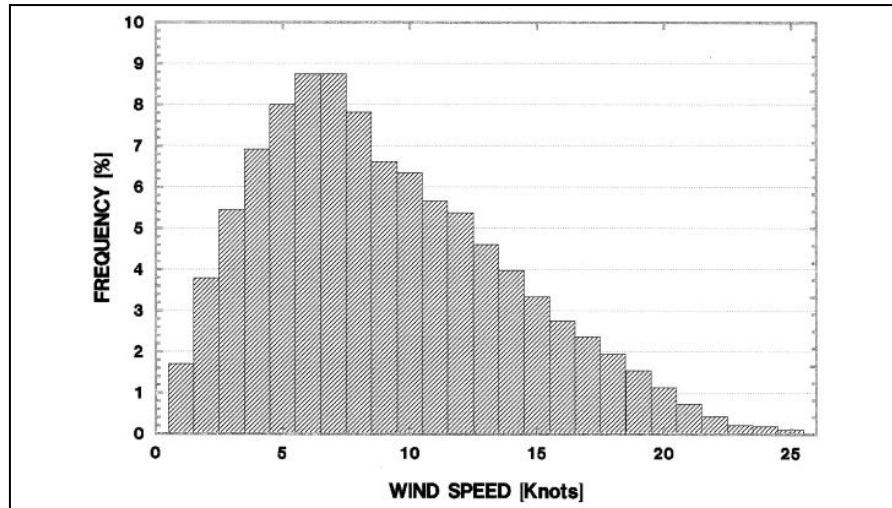


Figure (2)

Wind velocity frequency at Bahrain International Airport, Alnaser and Al-Karaghoul (2000).

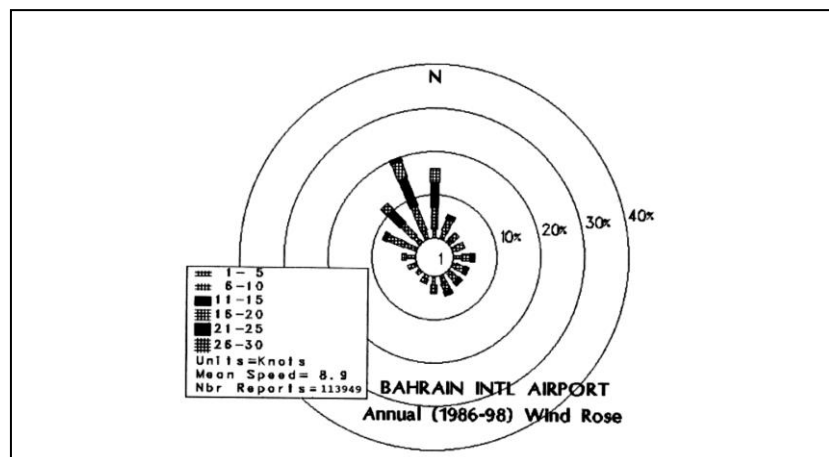
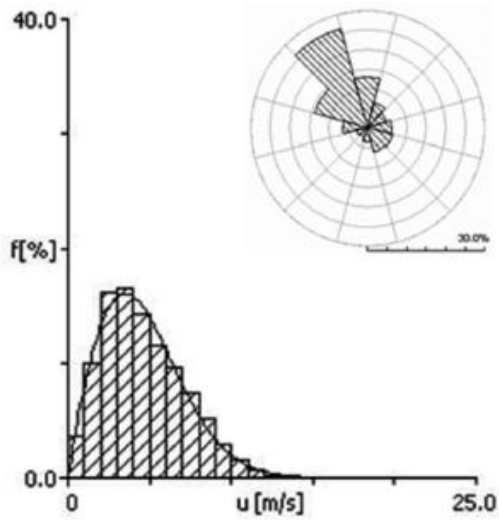


Figure (3)

Variation of wind velocity direction in Bahrain International Airport, Alnaser and Al-Karaghoul (2000).

A Goggle Earth picture of the bridge shows the direction and frequency of wind attacking from the northwest, as shown in Figure (4), Al Buflasa et al. (2008).

In this thesis, we will try to analyze the wind gusts from a repeated barrier as an environmental cause of directional instability of vehicles.



(a)



(b)

Figure (4)

a - Wind frequency and wind rose, b- wind rose attached on Goggle Earth satellite picture, Al Buflasa et al (2008).

1.2. Problem statement

When vehicles are traveling on the causeway in a windy condition, side wind disturbance will affect them as environmental disturbances which may result in directional instability. Thus, it is important to study the stability of vehicles in such conditions.

1.3. Objectives

- Simulate and quantify the variation of the aerodynamic distribution pattern of various crosswind velocities and orientations.
- Evaluate the effect on the stability of driver-vehicle closed loop system.

1.4. Significance of The Study

Local newspaper reports covered accidents involving different vehicle types (pickup trucks, motorcycles and sedans) while crossing the causeway on different dates throughout the year. Table (1) gives some examples of these accidents.

Table (1)
Local newspaper accident reports on the bridge

#	References	Date dd-mm-yyyy	Accident description	results
1	(Al-Wasat Newspaper 2003)	03-06-2003	1 vehicle lost control, cross to opposite direction and hit a light pole and 2 vehicles	4 injuries
2	(Al-Wasat Newspaper 2009a)	05-06-2009	1 vehicle hit a bicycle	1 death
3	(Al-Wasat Newspaper 2010)	20-06-2010	1 vehicle lost control, crossed to the opposite direction and hit a light pole and 3 vehicles	1 death 4 injuries
4	(Alayam Newspaper 2011)	31-12-2010	1 pickup truck lost control and crossed to the opposite direction and hit 2 vehicles	Several injuries
5	(Al-Wasat Newspaper 2011)	30-08-2011	1 vehicle lost control, hit a light pole and rolled over	5 injuries
6	(Al-Wasat Newspaper 2012a)	10-05-2012	1 motorcycle lost control	-
7	(Al-Wasat Newspaper 2012b)	15-06-2012	1 vehicle lost control	-
8	(Al-Wasat Newspaper 2012c)	23-11-2012	1 vehicle lost control	1 injury
9	(Al-Wasat Newspaper 2013b)	03-09-2013	1 vehicle lost control	2 injuries

The Ministry of Works in the Kingdom of Bahrain, based on instructions from His Royal Highness Prince Khalifa bin Salman Al Khalifa – the Prime Minister – responded to the increase of fatal accidents by taking precautionary

measures preventing vehicles from crossing over to the lanes in opposite directions. The measured cost was estimated at BD 296,000 in 2012 (Alayam newspaper 2012a), and (Alayam newspaper 2012b).

Statistics published in local newspapers (2008 - 2011) show a rapid increase in traffic on the causeway. Table (2) and Figure (5) generated from reported data in (Al-Wasat Newspaper 2013a) and (Al-Wasat Newspaper 2009b), which shows an increase of 59% in three years for this particular bridge.

Table (2)

Daily traffic statistics from local newspapers (2008 - 2011) generated from reported data in (Al-Wasat Newspaper 2013a, and 2009b)

Statistic year	Sh. Isa Bridge		Sh. Hamad Bridge		Sh. Khalifa Bridge		Total vehicles	
	No. of vehicles	% of total	No. of vehicles	% of total	No. of vehicles	% of total	No. of vehicles	% total increase
2008	44566	29.00	66081	43.00	43030	28.00	153677	-
2011	71000	32.13	85000	38.46	65000	29.41	221000	-
% Increase	26434	59.31	18919	28.63	21970	51.1	67323	43.81

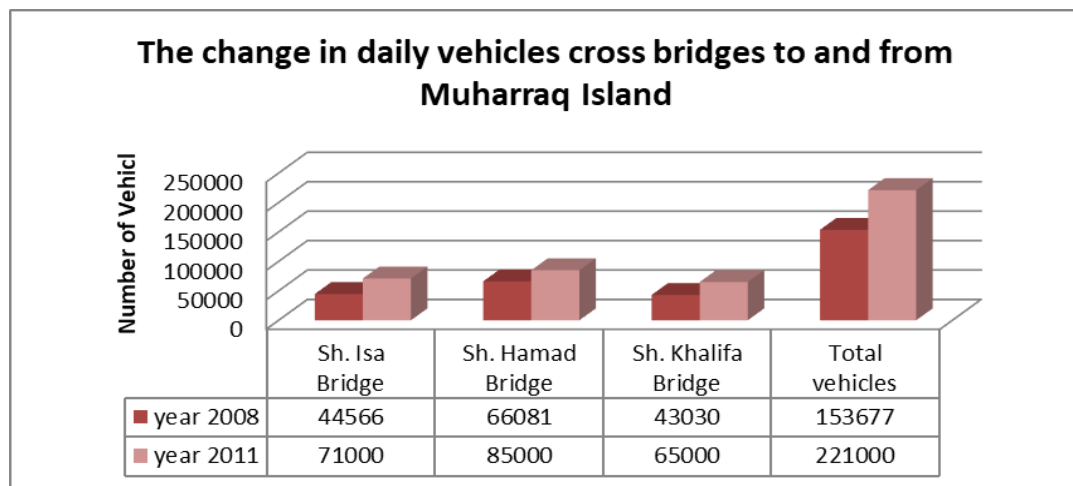


Figure (5)

The change in daily vehicles that cross bridges to and from Muharraq Island, generated from reported data in (Al-Wasat Newspaper 2013a) and (Al-Wasat Newspaper 2009b).

As a summary, the causeway is important to Bahrain's traffic, yet there are some real concerns about the safety of vehicles crossing the bridge. Per the author's knowledge, this is the first academic study conducted about the causeway problem as a case study.

Chapter 2

Theoretical Framework and Literature Review

Chapter 2

Theoretical Framework and Literature Review

2.1. Theoretical Framework

This theoretical framework provides a brief review of vehicle aerodynamics and vehicle lateral dynamics under cross wind conditions.

2.1.1. Nature of the flow in crosswind

The flow in the forward driving scenario with an absence of maneuvers or external disturbances around the vehicle is almost symmetric, where wind follows in a boundary layer with minimum or zero velocity near the ground. Figure (6) of (Cairns 1994) explains the nature of mixed flow towards the vehicle.

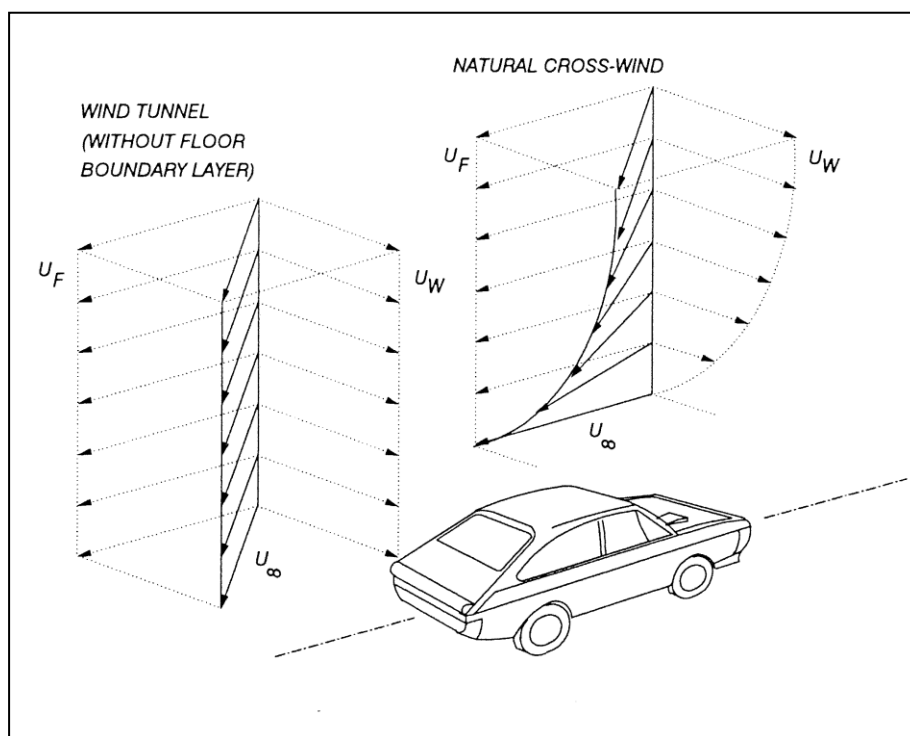


Figure (6)

Vehicle in Motion vs Wind Tunnel Wind Profiles (Cairns 1994)

The combination of the two flows depends on the vehicle velocity, wind velocity and wind direction Figure (7).

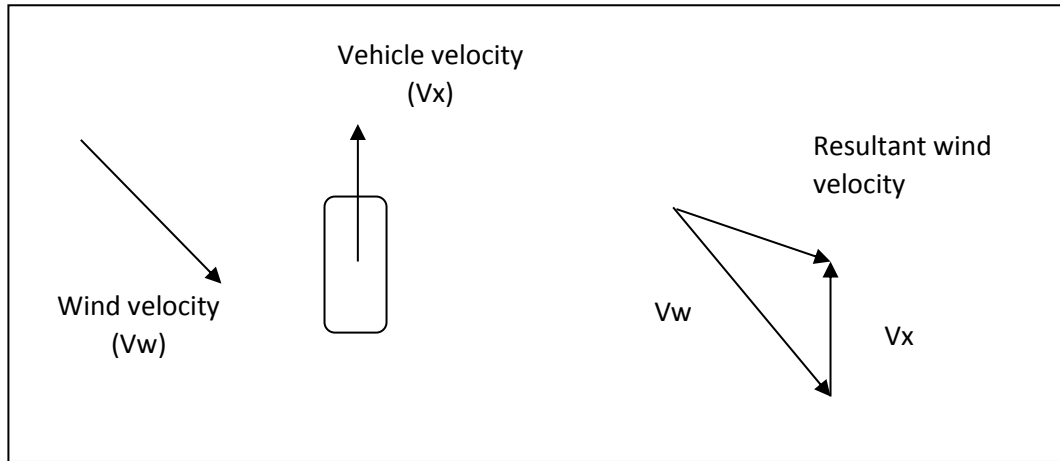


Figure (7)

Wind resultant from wind and vehicle velocities.

2.1.2. Vehicles Aerodynamics

In vehicle aerodynamics, the prime interest is to reduce the aerodynamic resistance which affects vehicle's fuel economy thus reducing undesirable exhaust emissions (Wong 2001).

In fluid mechanics, road vehicles are bluff bodies in very close proximity to the ground, as typical bluff bodies drag is mainly pressure drag. A road vehicles' shape is determined by functional, economic and aesthetic aspects. The aerodynamic characteristics are the consequence of the vehicle shape. (Hucho and Sovran 1993).

Drag is the force that acts parallel and opposite to the direction of vehicle travel, while coefficient of drag (C_d) is a common measure in design. It's an important parameter in any new vehicle design and should be take into consideration with other performance characteristics.

The force required to overcome drag force in forward motion is:

$$F_d = \frac{1}{2} * C_d * \rho * A * V^2 \quad 2.01$$

Where F_d is drag force, C_d drag Coefficient, ρ is air density, A is vehicle frontal area and V is vehicle forward velocity. Drag Coefficient (C_d) is used to evaluate the evolution in the vehicle's aerodynamics.

$$C_d = 2 * \frac{F_d}{\rho * A * V^2} \quad 2.02$$

The trend in the vehicle industry is to reduce C_d mainly due to its impact on fuel consumption as shown in Figure (8) from (Hucho and Sovran 1993).

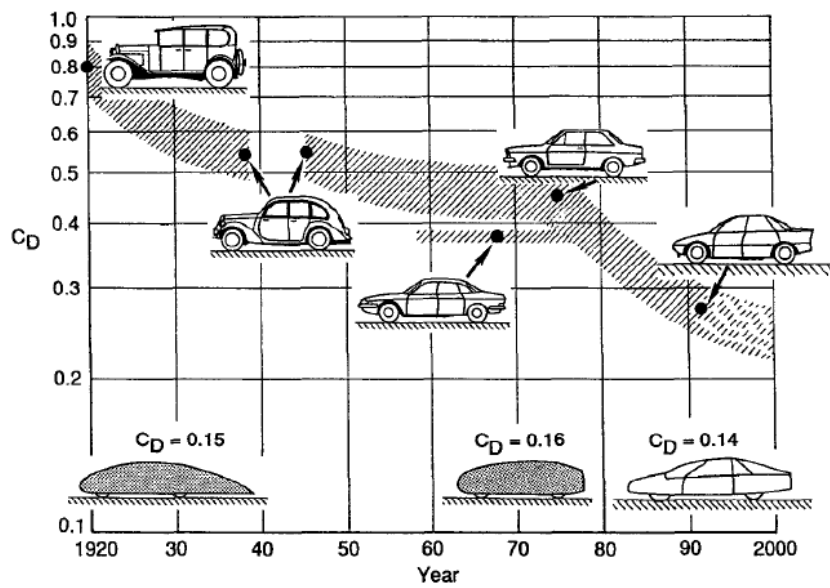


Figure (8):

The drag coefficient (C_d) history of cars. (Hucho and Sovran 1993).

Similar to lift and pitching moment on a wing at the angle of attack, wind generate side force and yawing moment on cars. A vehicle, when viewed from above, is similar to a blunt airfoil that generates side force when its angle of attack (yaw angle) is greater than zero.

Similar to drag force and C_d , side force (F_s) and coefficient of side force or (C_s) are used to study the side flow around vehicle where

$$F_s = \frac{1}{2} * C_s * \rho * A_s * V^2 \quad 2.03$$

and

$$C_s = 2 * \frac{F_s}{\rho * A_s * V^2} \quad 2.04$$

Where (A_s) is the side area of the vehicle.

A yaw moment (M_z) is a moment about the vertical axis of a vehicle and acts to change motion direction. Coefficient of yaw moment (C_m) is used to study the quantify the moment

$$M_z = \frac{1}{2} * C_m * \rho * A_s * V^2 * c \quad 2.05$$

and

$$C_m = 2 * \frac{M_z}{\rho * A_s * V^2 * c} \quad 2.06$$

Where (A_s) is the side area of the vehicle and (c) is the cord length, notice the only difference between Side force and yaw equations is the cord length (c).

The yaw rate of a vehicle (Ω_z) is the velocity or yaw velocity of this rotation, or rate of change of the heading angle, measured in radians per second or degrees per second.

Vehicle Lateral and yawing response in presence of wind disturbance is referred to as Crosswind Sensitivity. The key elements that crosswind sensitivity depend on are aerodynamic properties, vehicle dynamic properties, steering system characteristics and driver closed-loop steering behavior and performance (Gillespie 1992).

Crosswind sensitivity focus on the influences of various aerodynamic and vehicle parameters, as well as drivers' reactions in sudden crosswind gusts. On-road driving, computations and tests on the simulator have all led to a result that is important for aerodynamic development: yawing moment is more disturbing than side force (Hucho and Sovran 1993).

It is widely known that decreasing the weight of the vehicle and reducing drag is the trend in vehicle manufacturing to reduce material cost and improve fuel economy. These factors can contribute to handling problems at exposed sites during windy periods (Cairns 1994).

As for the angle between the travel axis and the resultant wind known as yaw angle (ψ), studies show different values of yawing moments and side force with the change in yaw angle. Figure (9) from (Hucho and Sovran 1993) shows that side force continues to increase with the increase of yaw angle, while yawing moment reaches its maximum between 20 to 30 degrees.

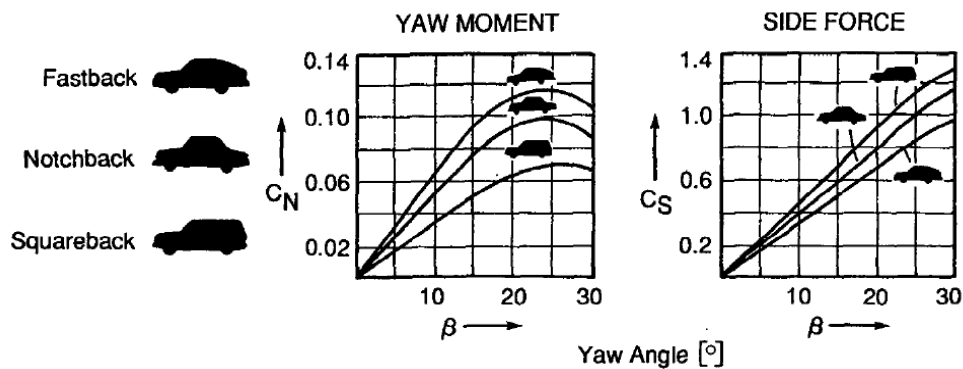


Figure (9)

Yaw-moment and side force coefficients in a family of cars with different rear-end shapes (Hucho and Sovran 1993).

2.1.3. Crosswind frequency

In case of steady crosswind, forces and moments on the vehicle will be almost steady, while this is not the case in gust wind or transient wind fluctuations due to barriers and bridge towers.

Several studies are available on the nature of wind on bridges without bridge towers like (Qi, Le-dong, and Zhen-Shan, 2010) and others cases with bridge towers like (Charuvisita, Kimura and Fujino 2004a), (Argentini et al. 2011) and (Rocchi et al. 2012).

This transient pattern of winds has a large frequency band; Sims-Williams (2001) summarized it as follows: High frequency unsteadiness due to random turbulence causes noise. Frequencies lower than (20 Hz) and above suspension natural frequency typically 1.0-1.5 Hz for European cars, can cause vibrations. Frequencies resulting from wakes generated by passing vehicle are close to vehicle suspension natural frequency; however, lower frequencies are the suspected cause of handling instabilities. Kozmar et al. (2012a) found maximum influence frequency of 1 Hz for both side force and yawing moments, and Wojciak (2012) placed it between 0.5 Hz and 4Hz experimentally.

In this case study, causeway triangular columns generate transient crosswinds different than mentioned works. Their cases have only one tower, yet our case has six barriers along its span. Wind is allowed to flow through the opening between barriers in addition to the barrier ends with a total of 7 wind gusts. As the span is constant, vehicle velocity will determine the frequency of wind gust as shown in the following equations.

$$Frequency = \frac{No. of wind gusts}{Time of crossing}$$

Or

$$Frequency = \frac{No. of wind gusts}{Span / Vehicle velocity}$$

At velocity of 30 m /s, it requires the vehicle 10 seconds to pass. With a frequency of 0.7 Hz, at velocity of 22 m /s, it takes 13.6 s, or 0.5 Hz. This shows that the bridge under study generate wind gust in frequency of effective frequency range.

2.1.4. Review of Vehicle Lateral Dynamics

Vehicles, as moving machines have different models, sizes and usages. Although the basic dynamics of wheeled vehicles are valid for all, here we reviewed the basic dynamics which are needed in our case study.

2.1.4.1. Tires

Aside from aerodynamic and gravitational forces, all other major forces and moments effecting the motion of a ground vehicle are applied through the running gear-ground contact (Wong 2001).

The tire is a simple visco-elastic toroid, and its properties belong to a very complex nonlinear system. More details about tire characteristics is given in appendix (A).

2.1.4.2. Handling characteristic of vehicle

The handling characteristics of a road vehicle refers to its response to steering commands and to environmental inputs that effect its direction of motion. There are two basic issues in vehicle handling:

1. Control of the direction of motion.
2. The ability to stabilize its motion direction against external disturbances.

The vehicle as a rigid body has six degrees of freedom, translations along the x, y, and z-axes, and rotations about these axes, Figure (10) and Table (3).

Table (3)

Vehicle axis System summery

	X-axis	Y-axis	Z-axis
Velocity	Forward velocity V_x (Longitudinal)	Lateral velocity V_y (Side)	Vertical velocity V_z (Normal)
Angular velocity	Roll velocity Ω_x	Pitch velocity Ω_y	Yaw velocity Ω_z

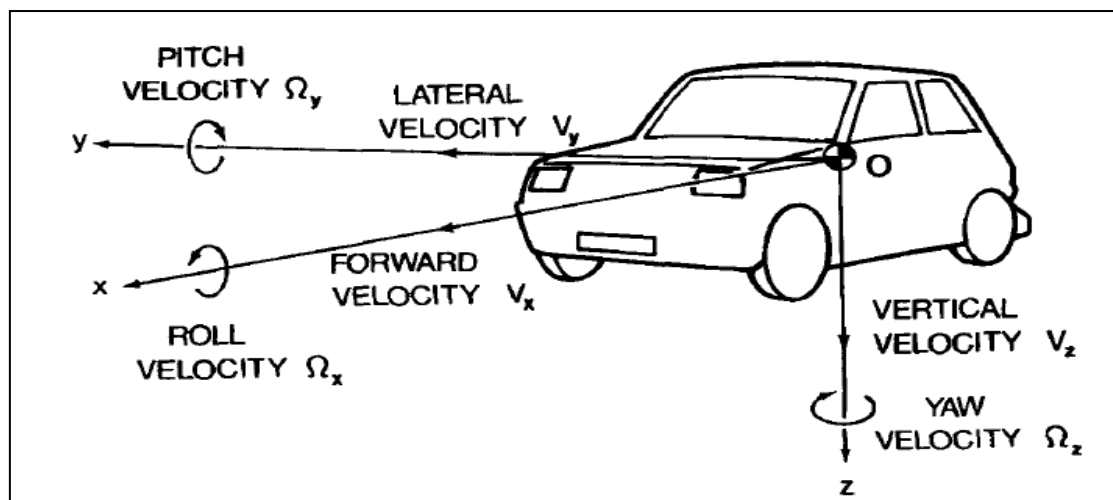


Figure (10)

Vehicle axis System (Wong 2001).

2.1.4.3. Transient response characteristics

The overall handling quality of a vehicle depends on its transient behavior, which is the behavior of the vehicle between the application of steering input and the attainment of steady-state motion. The behavior of the vehicle is usually referred as "transient response characteristics."

Inertia properties of a vehicle must be taken into consideration in analyzing the transient response.

2.1.4.4. Mathematical model of vehicle transient response

(This part summarized from (Wong 2001))

Let ox and oy be the longitudinal and lateral axes fixed to the vehicle body with the origin at the center of gravity, and let V_x , and V_y , be the components of the velocity V of the center of gravity along the axes- ox and oy , respectively, at time t , as shown in Figure (11). As the vehicle is in both translation and rotation during a turn, at time $t + \Delta t$, the change of the velocity component parallel to the ox axis is:

$$(V_x + \Delta V_x) \cos \Delta\theta - V_x - (V_y + \Delta V_y) \sin \Delta\theta$$

$$= V_x \cos \Delta\theta + \Delta V_x \cos \Delta\theta - V_x - V_y \sin \Delta\theta - \Delta V_y \sin \Delta\theta \quad (2.1)$$

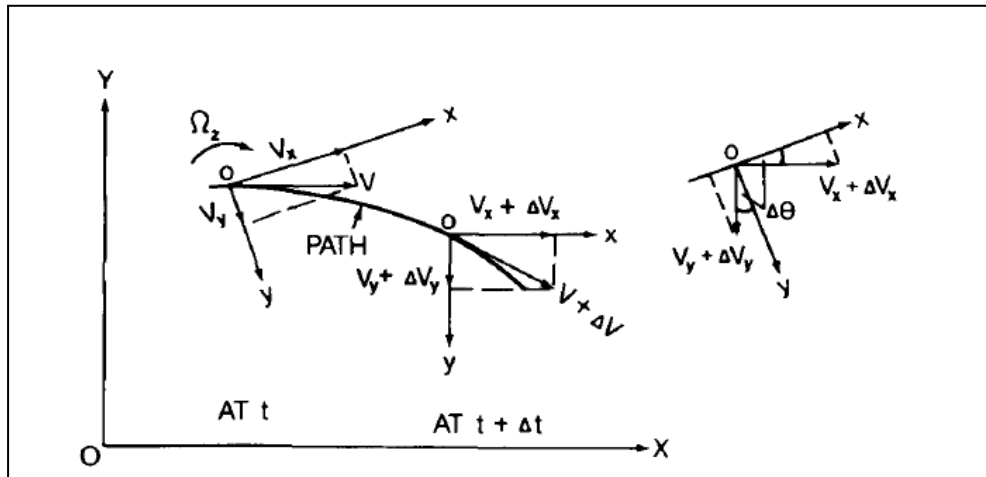


Figure (11)

Analysis of plain motion of a vehicle where the axis is fixed to vehicle body.
(Wong 2001)

Consider that $\Delta\theta$ is small, and neglect second-order terms

$$\Delta V_x - V_y \Delta\theta \quad (2.2)$$

$$a_x = dV_x/dt - V_y d\theta/dt = V_x^{\cdot} - V_y \Omega_z \quad (2.3)$$

Following a similar approach

$$a_y = dV_y/dt - V_x d\theta/dt = V_y^{\dot{}} - V_x \Omega_z \quad (2.4)$$

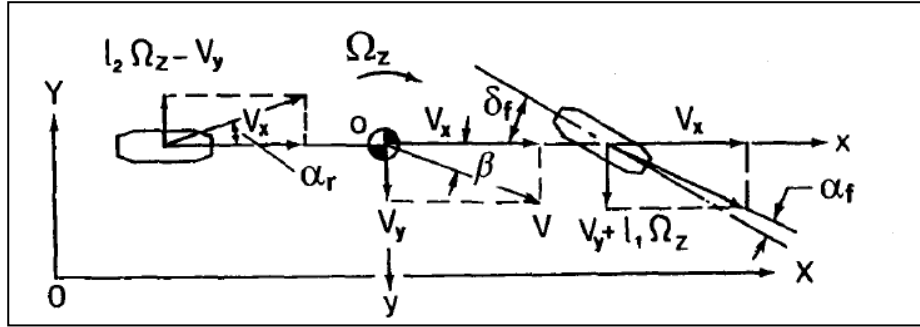


Figure (12)

Simplified vehicle model for analysis of transient motions (Wong 2001).

Referring to Figure (12), for a vehicle having plane motion, the equations of motion with respect to the axes fixed to the vehicle body given by

$$m (V_x^{\dot{}} - V_y \Omega_z) = F_{xf} \cos \delta_f + f_{xr} - F_{yf} \sin \delta_f \quad (2.5)$$

$$m (V_y^{\dot{}} - V_x \Omega_z) = F_{yr} + F_{yf} \cos \delta_f + f_{xf} \sin \delta_f \quad (2.6)$$

$$I_z \Omega_z^{\dot{}} = l_1 F_{xf} \cos \delta_f - l_2 F_{yr} + l_1 f_{xf} \sin \delta_f \quad (2.7)$$

Where I_z is the mass moment of inertia of the vehicle about the z-axis, it is assumed that the vehicle body is symmetric along the longitudinal plane and that roll motion of the vehicle body is neglected.

The slip angles α_f and α_r , defined in terms of the vehicle motion variables Ω_z , and V_y :

$$\alpha_f = \delta_f - (l_1 \Omega_z + V_y) / V_x \quad (2.8)$$

$$\alpha_r = (l_2 \Omega_z + V_y) / V_x \quad (2.9)$$

Lateral forces acting on the front and rear tires are a function of the corresponding slip angle and cornering stiffness expressed by:

$$F_{yf} = 2 C_{af} \cdot \alpha_f \quad (2.10)$$

$$F_{yr} = 2 C_{ar} \cdot \alpha_r \quad (2.11)$$

Combining equations 2.11 assuming that steer angle is small and F_{yf} is zero, the equations of lateral and yaw motions of a vehicle with steer angle as the only input variable become:

$$m \dot{V}_y + [m V_x + (2l_1 C_{af} - 2l_2 C_{ar}) / V_x] \Omega_z + [2C_{af} - 2C_{ar}] / V_x V_y = 2C_{af} \delta_f(t) \quad (2.12)$$

Or

$$\dot{V}_y + [V_x + (2l_1 C_{af} - 2l_2 C_{ar}) / m V_x] \Omega_z + [2C_{af} - 2C_{ar}] / m V_x V_y = [2C_{af} / m] \delta_f(t) \quad (2.13)$$

and

$$I_z \dot{\Omega}_z + [(2l_1^2 C_{af} + 2l_2^2 C_{ar}) / V_x] \Omega_z + [(2l_1 C_{af} - 2l_2 C_{ar}) / V_x] V_y = 2C_{af} \delta_f(t) \quad (2.14)$$

or

$$\begin{aligned} \dot{\Omega}_z + [(2l_1^2 C_{af} + 2l_2^2 C_{ar}) / I_z V_x] \Omega_z + [(2l_1 C_{af} - 2l_2 C_{ar}) / I_z V_x] V_y \\ = [2C_{af} / I_z] \delta_f(t) \end{aligned} \quad (2.15)$$

In the above equations, $\delta_f(t)$ represents the steer angle of the front wheel as a function of time. If, in addition to the steer angle, external forces such as aerodynamic forces acting on the vehicle are added to the right-hand side of last equations 2.12 and 2.14 as input variables, it became:

$$\begin{aligned} m \dot{V}_y + [mV_x + (2l_1 C_{af} - 2l_2 C_{ar}) / V_x] \Omega_z \\ + [2C_{af} - 2C_{ar}] / V_x V_y = 2C_{af} \delta_f(t) + \text{lateral force} \end{aligned} \quad (2.16)$$

$$\begin{aligned} I_z \dot{\Omega}_z + [(2l_1^2 C_{af} + 2l_2^2 C_{ar}) / V_x] \Omega_z + [(2l_1 C_{af} - 2l_2 C_{ar}) / V_x] V_y \\ = 2C_{af} \delta_f(t) + \text{yawing moment} \end{aligned} \quad (2.17)$$

When the input variables (steer angle, external disturbing forces, and initial conditions) are known, the response of the vehicle (in terms of yaw velocity Ω_z and lateral velocity V_y as functions of time) are determined by solving the differential equations of motion (Wong 2001).

2.1.4.5. Driver-Vehicle model

In driver-vehicle model, the driver acts as controller using visual tracking, comparing vehicle state to required state, finding a perspective and act throw steering, acceleration and deceleration. Yang (1999) classifies driver models into two groups based on tracking objectives: (a) compensatory tracking models utilize the path error only, and (b) preview tracking models, where the path error is minimized by predicting the future path using the preview effect.

Figure (13) shows a block diagram of the compensatory tracking model of a closed Driver-Vehicle system.

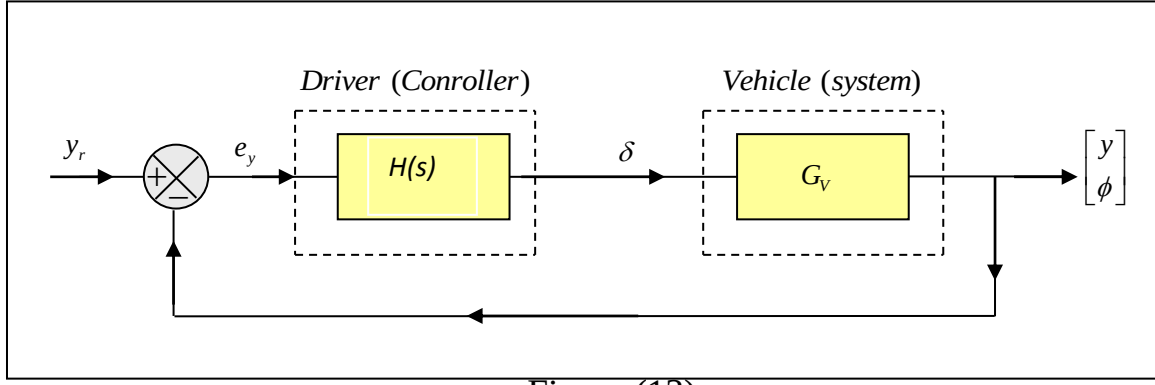


Figure (13)

Block Diagram of Driver-Vehicle Closed-Loop System

Yang (1999) summarized the reported compensatory tracking models in his work and found that a more sophisticated driver model does not necessarily yield more accurate response estimation than simpler models, A lead/lag compensator given by the transfer function $H(s)$ can be considered as a driver model,

$$H(s) = K \frac{T_L s + 1}{T_R s + 1} \quad (2.19)$$

Where K is the driver's gain, T_L is driver lead-time, and T_R is the reaction time. Where the drivers gain K ranges from a normal driving task (≈ 0.02 rad/m) to an aggressive steering task (≈ 0.2 rad/m).

The lead-time T_L should be greater than the reaction time T_R . The value of T_L could be in the range of (1 - 2 seconds), while T_R could reach 0.1 seconds for skilled and trained driver to 0.2 seconds for ordinary driver.

For the vehicle model, literature mentioned different models depending on number of degrees of freedom (DOF), wherein the two DOF is the simplest representation of vehicle motion.

The block G_V , shown in Figure (13), represents the vehicle dynamic transfer function. The vehicle model may be represented by state-space format.

This approach gives a straightforward way to analyze multiple-input and multiple output systems. State-space models help to demonstrate controllability of systems.

2.2. Literature review

In this review, the crosswind effects studies are divided into two outlines:
(a) vehicle aerodynamic studies conducted mainly to find forces and moments from gust wind mathematically, experimentally and computer simulations, and
(b) lateral stability dynamics of vehicles studies. Some literature contains both.

2.2.1. Vehicles crosswind aerodynamic literature

The earliest studies started in the 1960's, and the Society of Automotive Engineers (1965), pointed out the importance of this problem. Wind acting on a vehicle will approach from a variety of angles relative to the longitudinal axis, unless it is windless or wind direction is parallel to the vehicle's forward motion (Society of Automotive Engineers 1965), the same reference also indicated that side force is generated by pressure difference, Figure (14).

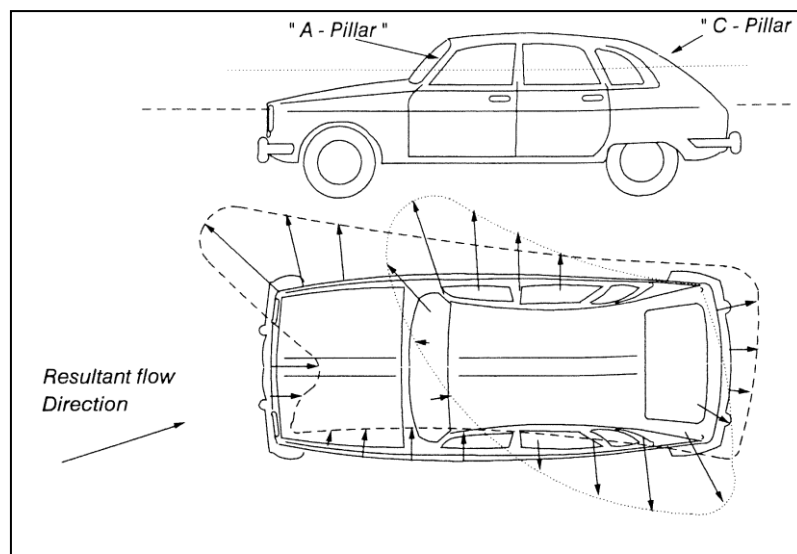


Figure (14)

Schematic Diagram of the Surface Static Pressure Distribution Around a Typical Car Subjected to a Steady Crosswind (Cairns 1994).

In this review, only literature from 1990 upward will be reviewed. Among the important works, C. J. Baker published a series of papers starting in the 1980s;

the most important of them is the three-part paper (Baker 1991a, b and c). In Part I, Baker (1991a) set new analytical framework that enables the inter-relation between the various cross wind problems, and discusses the mean aerodynamic forces and moments for a variety of vehicle types for high and low velocity trains, high-sided road vehicles and cars. In Part II, Baker (1991b) considered the unsteady aerodynamic forces and moments on such vehicles. In Part III Baker (1991c) considered the interaction between the applied aerodynamic forces and the dynamics of the vehicle system.

Humphreys and Baker (1992) investigated and measured the aerodynamic forces and moments on 1/50th scale lorry model vehicles in cross winds using an experimental rig that propels vehicle models across an environmental wind tunnel. The results highlighted the importance of modeling both atmospheric turbulence and vehicle motion when attempting to measure cross wind forces on ground vehicles.

Hucho and Sovran (1993) summarized the academic work of Hucho and the practical industrial experience of Sovran in an annual review, and utilized more than 100 references sited up to 1992. The review included CFD works on vehicle aerodynamics, and stated some open issues, recommending that crosswinds sensitivity must be kept under control by reducing yawing moment and side force as future trend.

Coleman and Baker (1993) carried out environmental wind tunnel tests on a 1/50th scale articulated lorry model on a bridge deck with and without a simulation of atmospheric turbulence. The study found that unsteady flow measurements indicated that side force oscillations are largely caused by turbulence buffeting while lift force oscillations dominated by large-scale unsteadiness are caused by wake vortex shedding.

Cairns (1994), in his Doctoral thesis, used a Cranfield University crosswind facility to design and test a 1/6 scale model to measure the forces and moments in dynamic and static tests. He found that quasi static experiments will not provide an adequate engineering estimate of the transient aerodynamic loads.

Humphreys (1995), in his Doctoral thesis, reported moving model rig tests and static model tests of a 1/50th scale lorry and 1/45th railway container vehicles. The measured forces from the static tests compared with the moving model rig tests showed a large difference. It was found that the normalized extreme force parameter measured for yaw angles above 30 degrees implies quasi-steady behavior; however, for lower yaw angles some body-induced unsteadiness is evident.

Sigbjornsson (1998), used a probabilistic reliability approach to assess wind related accidents of road vehicles as a tool to improve design of roads and highways for traffic safety in windy environments by pointing out potential accident spots.

Chadwick (1999) in his Doctoral thesis, used a Cranfield University crosswind facility wind tunnel, in (Cairns 1994), to test 1/8 scale static and dynamic models. A flat plate, sharp edge box, radiused edge box and Rang Rover model were tested. The results show that the change in vortices produce peak yawing moments up to double the steady state tests.

Ryan (2000), in a Doctoral thesis, used a University of Durham transient crosswind facility to experiment with two static models using the static dynamic method (i.e. static model dynamic wind). Two aerodynamic models: Docton Geometry for 2-d test and Durham Geometry for 3-d test were both subjected to

transient crosswind. Trial to CFD for the 2-d was abandoned because of difficulties. A CFD study only done for the empty working suction. Models exhibited transient force and moment overshoots, and these were found to be a consequence of delayed pressure which confirms the requirement for transient testing.

Sims-Williams (2001) in his Doctoral thesis, stated that a range of 2-dparametric two-dimensional bodies have been used to develop novel experimental techniques, including new 2-d similar to Docton model, 2-d and 3-d Ahmed model and Rover 200 model in wind tunnels at Durham and at MIRA at scales of up to 40%. CFD simulation was done only for the models 2-d and 3-d except Rover 200, and then used as a comparison to validate the CFD technique that was done.

Favre (2009), in his Licentiate thesis, conducted a CFD investigation of unsteady crosswind aerodynamics for 3-d models: sharp edge box, radiused edge box were both used in (Chadwick 1999), and Windsor Model that provided a more realistic ground vehicle geometry. The aim was to explore the possibilities offered by Detached-Eddy Simulations (DES) technique to simulate unsteady crosswind aerodynamics of simple vehicle models. The (DES) technique was found to be promising and overall proved compatibility with experiments.

Favre in his doctoral thesis (2011) continued his work by testing DES types of grids, numerical setups and refinements. A static coupling between DES and vehicle dynamic simulation of road vehicle models was performed. He showed that the center of pressure motion with respect to the center of gravity and the neutral steer point is of prime interest to design vehicles that are less crosswind sensitive.

Wojciak (2012) conducted experiments in wind tunnels with realistic vehicle scale of 1:2 oscillating around its vertical axis exposed to time dependent flow conditions. Experimental results were used to validate a CFD simulation tool with the rotational sliding mesh technique. He verified that a delayed reaction of the wake flow to a change in the oncoming flow leads to an increase in total unsteady yaw moment amplitude and decreases the total side force amplitude.

Suzuki et al. (2002) evaluated the aerodynamic characteristics of train vehicles in three kinds of wind tunnel tests made on typical configurations of infrastructures such as bridges and embankments. The side force coefficient of a vehicle tend to increase as the thickness of the bridge girder becomes larger. It also increases as the roof of the vehicle becomes more edgy.

Charuvisita, Kimura and Fujino (2004a) presented an experimental model scale 1:30 model of a vehicle passing in the wake of a bridge tower herein static and dynamic results are compared and the general analytical prediction procedures are presented. Charuvisita, Kimura and Fujino suggested a wind barrier for the problem in (2004b), the effects of the barrier on the characteristics of wind distribution and the aerodynamic forces experimentally and analytically presented. Vehicle response was found to be larger due to increased wind and vehicle velocity, and reaches maximum when wind attacks from 30°. The effects of the wind barrier were found to be effective.

Pinelli et al. (2004) tried to set a critical velocity for typical fire trucks, ambulances and sports utility vehicles which reduced scale models tested in a wind tunnel and surface pressures and overall forces measured. The overturning and course deviation occurrence on wet and dry roads was presented. Based on the results, safe wind velocities were defined for the operation of these fire and rescue vehicles.

Noger et al. (2005) investigated the transient aerodynamic phenomena associated with passing maneuvers experimentally. Results indicated unsteady aerodynamic effects appear in an overtaking vehicle while effects between the vehicles vary as a linear function of the transverse spacing.

Yun et al. (2006) presented a CFD study on the interactions between rail vehicle and suggested wind fences under strong crosswinds. The results showed reduction in aerodynamic forces as the fence height increase.

Bocciolone et al. (2008) compared and confirmed wind tunnel tests on the first two vehicles of train 1:20 scale models by CFD numerical simulations tests, and showed that the aerodynamic coefficients in high angles of attack are significantly influenced by turbulence characteristics.

Argentini et al. (2011) used wind tunnel tests to measure the aerodynamic loads and the surface pressure distribution on a 1:40 scale long vehicle model when it crosses the wake of a bridge tower. A description of the aerodynamic phenomenon is proposed.

Cheli et al. (2011a) investigated the sensitivity of steady and unsteady aerodynamic forces acting on a high-sided lorry model in different test conditions. Wind tunnel experiments on a 1:10 static scale investigate the unsteady force/moment component. Moreover, Cheli et al. (2011b) Part 2, investigated the influence of the infrastructure scenario (flat ground, embankment, single and double viaduct) on other heavy vehicles (tank truck, tractor–semitrailer combination and tractor–trailer combination) to assess the influence of the vehicle geometry.

Rocchi et al. (2012) applied an experimental–numerical approach for simulating the aerodynamic forces acting on a moving vehicle passing in the wake of a bridge tower under crosswinds. They aimed to simulate the effects on handling by studying the interaction between the aerodynamic forces and the

vehicle–driver behavior. They found that wind fences are able to reduce rollover risk, but may generate a suction effect requiring large corrections on the steer angle to the driver model.

Zhu et al. (2012) presented a stationary vehicle model in wind tunnel tests carried out to determine aerodynamic coefficients of four types of 1:25 scale road vehicles over a typical bridge deck with different wind directions. Results showed that the existence of a bridge deck reduces side force but increases rolling moments.

Dorigatti et al. (2012) also presented a stationary vehicle model wind tunnel for three different vehicles 1:40 scale model (a van, a double deck bus and a lorry) on two different bridge decks with different wind direction. They indicated that the lorry, rather than the van or the bus, is the critical vehicle in terms of overturning stability.

Kozmar et al. (2012a) carried out wind tunnel experiments to investigate transient aerodynamic loads on vehicles running on bridges using a generic van model at the scale of 1:40. Wind generated airflow represents bora type winds. The mean side force and the overturning moment of the vehicle was found to increase in a linear direction with an increase in the gust velocity.

Kozmar et al. (2012b) tested sheltering efficiency of wind barriers experimentally in a boundary layer wind tunnel as a solution. They found that without a wind barrier, wind velocities on bridges reach 80% of the freestream velocity at heights as low as one meter.

Cheli et al. (2013) presented wind tunnel static tests that resulted in a train vehicle (MLA Riyadh vehicle) 1:15 scale model. They found that atmospheric winds characterized by higher integral length scales produced higher loads on the vehicle both in terms of lateral and vertical force and of rolling moment.

Computational Models of Vehicle in Crosswind.

Khier et al. (2000) presented a 3-d numerical study of the flow structure around trains under side wind conditions. They found that at small yaw angles, strong variations of the pressure take place resulting in a longitudinal variation of the forces and moments.

Bettle et al. (2003) performed 3-d analysis using a commercial CFD program called Flovent to examine the effect of truck velocity on the aerodynamic forces acting on a standard sized transport truck travelling across a bridge under crosswind conditions. The results showed that the aerodynamic moment tended to overturn a truck from approximately 120kNm at low velocities to 217kNm at a truck velocity of 120 km/h. 82 and 154kNm, respectively.

Corin et al. (2008) developed and applied 2-d CFD methods to study the aerodynamic forces on overtaking road vehicles that maneuver in the presence of crosswinds. The linear sliding mesh technique used and PARAD1 and PARAD2 geometry of (Sims-Williams 2001) experimental results were obtained and compared with the dynamic forces which were found to be up to 400% greater than quasi-steady analysis.

Tsubokura et al. (2010) applied large eddy 3-d CFD simulation to find the unsteady aerodynamic response of a road vehicle subjected to transient crosswinds validated with 1/20 scale wind-tunnel model in static, and was applied on to two transient crosswind situations: a sinusoidal and a stepwise crosswind velocity. They noticed that such transient aerodynamic forces are difficult to measure using a conventional wind tunnel.

Guilmineau et al. (2011) presented a crosswind simulation around the square-back Willy model for several yaw angles with a finite volume based Detached-Eddy Simulation (DES) for the prediction of flow around a passenger

vehicle. The results compared to a previous numerical study based on a RANS simulation and experimental data showed that DES simulations provide a better agreement with experimental data.

Nakashima et al. (2013) presented a fully coupled analysis of vehicle motion and the transient flow around the vehicle using a large-eddy simulation (LES) technique applied to reproduce the unsteady turbulence motion of a full-scale truck vehicle. A parallel analysis of the dynamic effect and position on the vehicle was done simultaneously. The results were compared with those of a conventional quasi-steady analysis, and certain differences were identified. The effects of the transitional aerodynamics on variables related to driver's perception are significant.

Uystepruyst and Krajnovic' (2013) presented a 3-d CFD simulation of the transient aerodynamic phenomena induced by passing maneuvers in the absence of a cross wind. The results were found to agree well with the existing experimental data.

Chu et al. (2013) used wind tunnel experiments and a CFD with a Large Eddy Simulation (LES) model to investigate the protective effect of porous windbreak on road vehicles against crosswind. The shielding effect of the wind break height of 2m plus the barrier of 0.8 m height was found sufficient to protect the vehicle with 3.6 meter height.

William et al. (2013) presented a 3-d static CFD analysis of a passenger bus to investigate the change in the aerodynamic forces in a crosswind in the case of a 45° yaw angle. The study introduced a lift coefficient higher than double the drag coefficient value in the case of pure front wind and a side force coefficient greater than seven times the reference drag coefficient in pure front wind conditions.

Wang et al. (2014) studied the crosswind effect on road vehicle passing a bridge tower with similar 3-d CFD using dynamic mesh through wind tunnel investigation. The result showed a sudden change in force time which may be shorter than the average driver reaction time.

2.2.2. Vehicles Directional Dynamics Literatures.

The following literature is about vehicle dynamics and dynamic lateral stability under crosswind conditions. Literature that contains both aerodynamic and dynamic stability is mentioned in the previous part of the review.

Wong (2001) set the detailed equations of vehicle transient response characteristics for external disturbances, and he also set criteria for directional stability; however, crosswind sensitivity terminology was not in this reference.

Gillespie (1992), in his book, set detailed equations for vehicle dynamics and stability. Furthermore, in chapter (4), the author discussed in details the fundamentals and set formulas for aerodynamics forces and moments along each axis. The crosswind sensitivity was included.

MacAdam (1989) set a formulation to represent the static turning response of a vehicle due to applied external or control forces. Later, he used the formulation in MacAdam et al (1990), where they conducted vehicle crosswind research involving both full-scale driver-vehicle tests and associated analyses with different driver preferences.

Vehicle lateral stability and control of driver-vehicle was studied in several previous works where computer programs were used to give robust steering control (Habib 1996 and Habib 1997). The work continues to find the Optimum Vehicle Parameters Based on The Pilot-Vehicle Directional Stability (Habib et al., 1993).

Yang (1999), in his PhD dissertation, presented a comprehensive closed-loop driver-vehicle directional dynamics predictor for heavy vehicles, where he studied the control demands imposed on the driver with functions of selected operational and environmental factors. One of the results is that a more sophisticated model does not necessarily yield more accurate responses estimated in simpler models due to cumulative effects of errors in a large number of input parameters.

Guo et al. (2003), established a directional control driver model with efficiency, accuracy and driver preference. Numerical simulations in typical maneuver are studied.

Juhlin (2004) investigated directional stability of buses under the influence of crosswind gusts, and was an MBS-ADAMS vehicle model combined with a generalized crosswind gust model that resulted from static wind tunnel measurements. The investigation showed the importance of load distribution and driver reaction time in the simulation.

Maruyama, and Yamazaki (2006) investigated the moving stability of a vehicle under strong crosswinds based on numerical analyses and driving simulator experiments. They stated that if the model driver's reaction parameters are properly determined, crosswind responses of a vehicle could be simulated using the numerical model without actual vehicle tests or driving simulator experiments.

Juhlin (2009) assessed in the PhD thesis, the crosswind sensitivity in different chassis-related and aerodynamics-related parameters of buses. The results identified the location of center of gravity and the yaw moment overshoot at gust entry as areas of high potential for improving the crosswind sensitivity of buses.

Fuller et al. (2013) developed a vehicle model and studied the effect of two time-dependent crosswinds on a windy day and during extreme crosswind gust. A quasi-static response was considered with five sources of aerodynamic unsteadiness. The results showed that the largest effects of simulated unsteadiness are due to the relatively low frequency of time-dependent wind inputs.

Yakub, et al. (2016) presented a comparative study of model predictive control approaches of two-wheel steering (2WS), four-wheel steering (4WS), and a combination of two-wheel steering with direct yaw moment control (DYC) maneuvers for path-following controls in autonomous car vehicle dynamic systems. They found that model predictive control was useful to maintain vehicle stability and able to eliminate crosswind effect.

William et al. (2014) used the results from an earlier paper (2013), to analyze vehicle lateral dynamics with a 2-dof MATLAB model executed in a MATLAB Simulink environment. Results showed that in case of 25 m/s wind gust to 45° relative yaw angle, the vehicle's lateral deviation maintained about 5 m after 4.5 seconds of entering the wind gust.

2.2.3. Summary

The literature survey showed different methods to simulate the crosswind effects, from experimental (static and dynamic) models to full-scale studies.

With the increase of a computer's capabilities and the availability of CFD programs, new methods been used to simulate the vehicle's crosswind gust problems.

Dynamic response of vehicles and their stability were studied through computer software (like MATLAB and Simulink) to find optimum solutions for vehicle directional stability.

The previous studies are classified as follows:

- 1- Mathematical models.
- 2- Experimental models, Cairns (1994) classify them as:
 - i- Scale model static wind tunnel tests.
 - ii- Scale model dynamic wind tunnel tests.
 - iii- Full-scale test.
- 3- Computational models.
 - i- 2-d CFD.
 - ii- 3-d CFD.
 - iii- Vehicle simulator.

From the general overview, there is enough previous research to compare our research results; experimental dynamic models are less available than static models.

From the literature, the following points are concluded:

- Literature studied vehicle-crossing bridges with only one column as a wind barrier, where as in this thesis multiple barriers are presented as a case study.
- 3-d and 2-d CFD techniques were used in the literature; however, 3-d models need more time and computational resources. Because experimental results of 2-d are available for validation, this format was chosen for this thesis.
- A 2-d sliding mesh technique was used and validated in the literature. The technique chosen for this thesis is expected to give adequate results.
- As a limitation of using 2-d CFD, some forces will not be included, such as lifting force, pitching and rolling moments. These forces have effect on vehicle traction and stability.

- Literature that evaluates vehicle dynamic stability, mainly assessing lateral deviation and angular deviation, stated that more sophisticated models do not necessarily yield responses that are more accurate. In this thesis, a lead/lag compensator is used to represent driver behavior.

Chapter 3

Methods and Procedures

Chapter 3

Methods and Procedures

3.1. Methodology of Assessing Aerodynamic Parameters

In the computer simulations used in this thesis, the study is divided into two parts; (a) finding the aerodynamic forces developed by the sails of the bridge, and (b) finding the effect of forces on lateral dynamic stability.

Two different numerical platforms are used; CFD code Fluent Ansys® for the aerodynamic part and MATLAB Simulink® for the dynamic part. The data is transferred between the two platforms via a spreadsheet. Other programs that are used are listed in procedures of Figure (15).

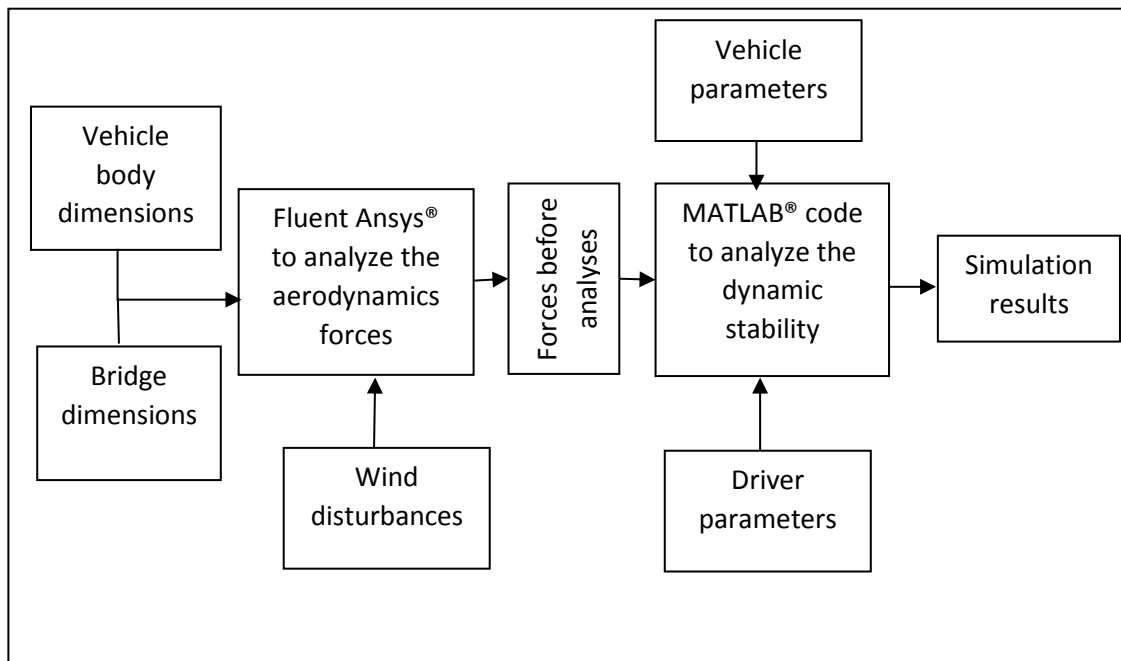


Figure (15)

Summary of Methodology.

One of the commercial codes in market for research and industry is Fluent[®], which comes in an Ansys[®] platform. Many researchers cited in chapter 2 used Fluent[®] to solve or validate experimental finding Fluent[®] is used in this study to simulate the aerodynamic force on a vehicle.

3.1.1. Procedures of aerodynamic parameters investigation

In order to evaluate the change of aerodynamic loads on a vehicle passing over the bridge of interest, a 2-d finite element model was built using actual bridge dimensions and assumed vehicle dimensions. A sliding mesh technique tested in a defined vehicle and wind velocities. However, before using a 2-d CFD model with the new technique, a validation of both the model and the technique are needed.

3.1.2. Vehicle 2-d model and mesh design validation

The vehicle model used in validation is identical to the 2-d experimental model of Sims-Williams (2001), geometry shown in Figure (16) is 1:10 scale used for validation which Corin et al. (2008) used for their CFD investigation.

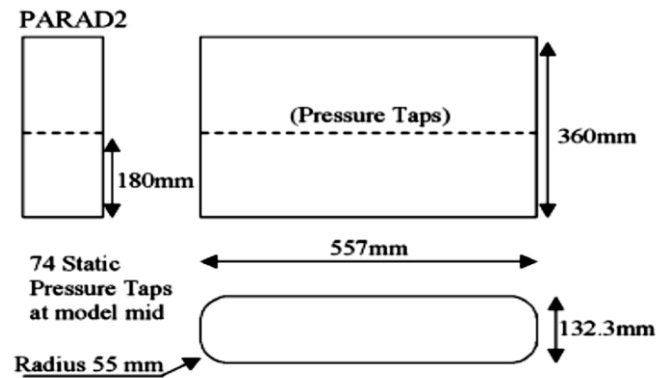


Figure (17)

Vehicle geometry used in Sims-Williams (2001).

Steps of the vehicle model and mesh design validation are shown in Figure (17). Mesh design and boundary conditions used in validation were similar to the Corin et al. (2008) setup; Figure (18) explains the mesh design

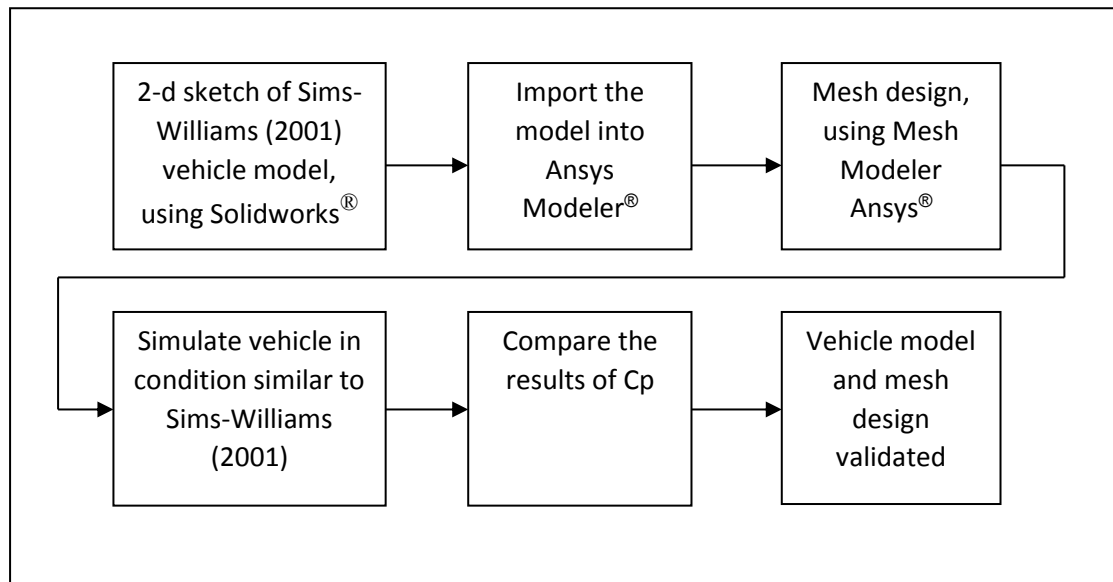


Figure (17)

Steps of vehicle model and mesh design validation

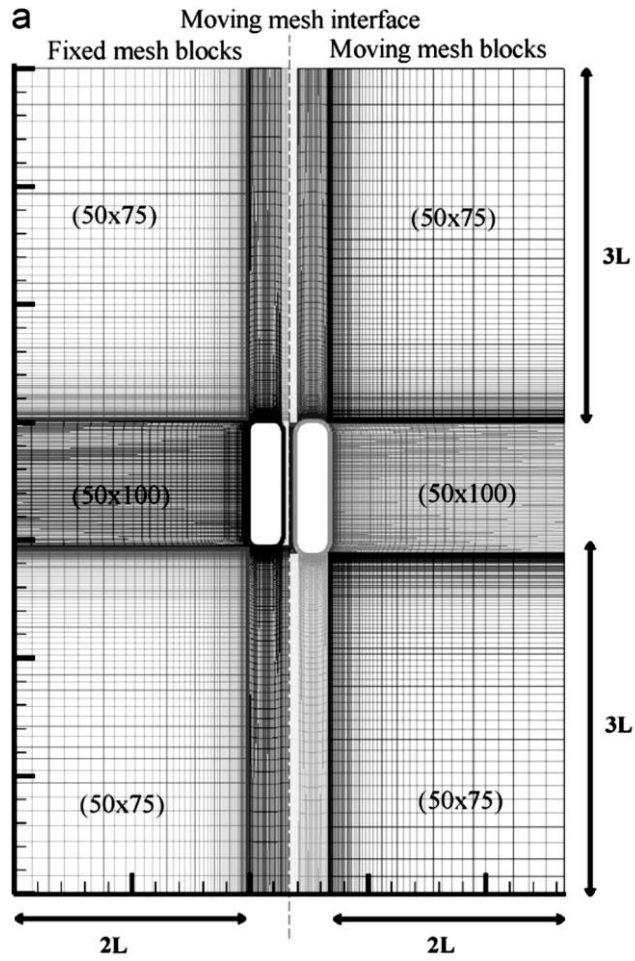


Figure (18)

Computational mesh Corin et al. (2008).

3.1.3. Sliding mesh technique validation

In this study, a time-accurate solution with instantaneous interaction is needed. Sliding mesh technique is an accurate method for simulating flow in moving zones relative to each other, but it demands a large computational capability.

There are two types of sliding mesh techniques: rotational and translational relative motion. Rotational sliding is suitable to simulate cases that involve rotor-stator problems (e.g. turbines and pumps). Translating sliding mesh zones are used for trains passing a wall or cars overtaking maneuver, as shown in

Figure (19). The main idea of the technique is to state two or more zones moving relatively to the other, and there is interface between them.

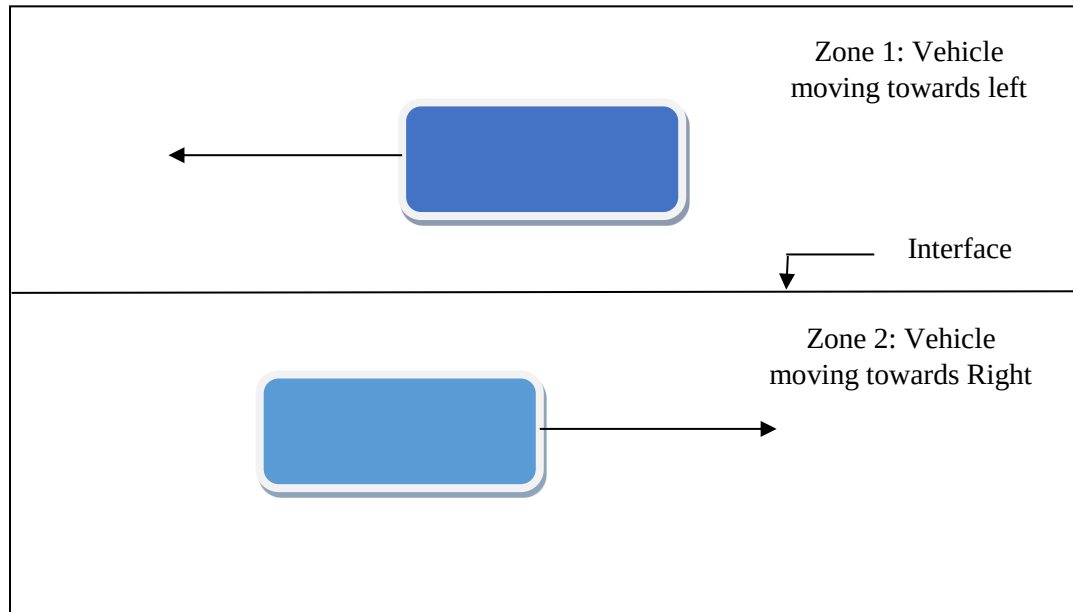


Figure (19)

Sketch represents two passing vehicle problems: separated zones and interface used in sliding mesh technique.

The mesh of each zone is created separately because the technique uses the flux in the interface calculation. Node or finite element cell alignment is not required along the mesh interface.

Repeating Corin et al. (2008), CFD experiments assessing overtaking maneuvers, using Fluent Ansys® ability of translational sliding mesh, are used to validate the technique. The parameters used in validation are C_d and pressure fields for overtaking maneuvers with a wind yaw angle of -20 degree of PARAD2 model at relative velocity $V_r = 13.4$ m/s. The steps of validation are shown in Figure (20). Details of validation procedure in Appendix (B): Steps of repeating Corin et al. (2008) CFD experiment.

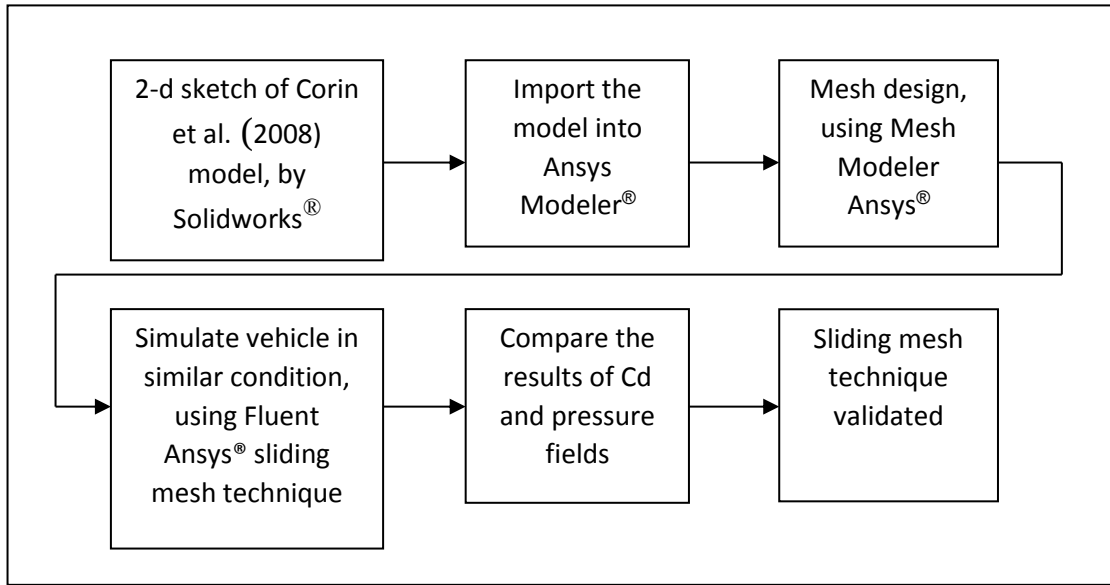


Figure (20)

Steps of sliding mesh technique validation.

3.2. Aerodynamic forces simulation procedure

Numerical simulations were conducted using commercial ANSYS solver FLUENT®, Version 14.

3.2.1. Coordinate system.

A global coordinate system is different than the coordinate system explained in Chapter (1) in Table (3) and Figure (10). To remove misunderstanding due the simulation arrangement, Figure (21) shows the coordinate system used with the problem setting.

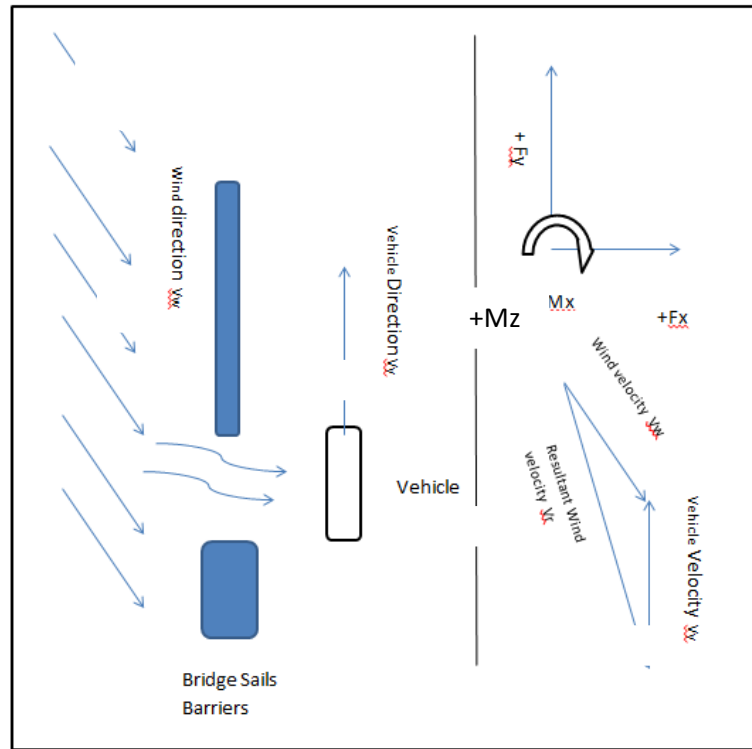


Figure (21)

Coordinate system used with the problem setting.

3.2.2. Vehicle and Bridge Geometry

Vehicle models were used identical to the 2-d experimental model of Sims-Williams (2001); which Corin et al. (2008); used for their CFD investigation. The geometry shown in Figure (15) is 1:10 scale used for validation. A full-scale geometry was then used in the CFD, Table (4) to list the dimensions used.

Table (4)

Vehicle and Bridge dimension.

#	Geometry	Length	Width	Corner
1	Vehicle	5.57 m	1.323 m	Radius 0.55m
2	Bridge sails	24.5 m	0.6 m	Right angle
3	Bridge column	4 m	1.5 m	Right angle

3.2.3. The bridge and vehicle sketch

The sketch consists of three zones bridge, vehicle and after vehicle zones. Zone models were generated using Solidworks® separately, and saved on a STEP format file before being upload it to Fluent® Geometry Modeler®, see Figure (22). The dimensions and outer boundary conditions of the three zones are listed in Table (5). The vehicle and bridge body are represented as a wall with an empty area inside because no flow to cross them is assumed.

The size of the computational domain was set as the real road lane's width and the sails length at the beginning. After running the simulation, an additional length was needed to capture the changes in the flow at the entrance and exit of the bridge. Sufficient distances added between the vehicle and sails that extend the boundary in length.

Table (5)

The dimensions of the three zones.

Zones	Represent	Width	Length
First zone	Bridge sail barrier	19.5 m	344 m
Second zone	Vehicle in the first lane	12 m	1046 m
Third zone	After Vehicle	12 m	344 m

Moreover, to investigate the effect of different wind velocities, velocity of crosswind velocity of (0, 10, 20 and 30 m/s) at a 90° angles was tested. To investigate the effect of vehicle velocity, 22.22 m/s, 27 m/s and 33.33 m/s velocities were tested. A list of all conditions tested are available in Table (6).

Table (6)
List of Vehicle velocity and wind velocity and direction tested.

#	Vehicle velocity (vehicle zone translation in y-axis)	Wind velocity (m/s)	Wind direction (Compared to vehicle travel direction)
1	97.2 km/hr. (27 m/s)	0	-
		10	90°
		20	90°
		30	45° , 60° and 90°
2	80 km/hr. (22.22 m/s)	30	90°
3	120 km/hr. (33.33 m/s)	30	90°

3.2.5. Technical setting for simulation.

The technical procedure of aerodynamic simulation using ANSYS Fluent[®] software is mentioned in detail in Appendix (C).

3.2.6. Data processing

The software only gives the coefficient's history value. Calculation is needed to adjust the reference value and to find the forces history.

The following section will discuss vehicle dynamic stability methodology, and results of both section presented in chapter (4).

3.3. Methodology of assessing the Vehicle lateral dynamic stability

The results of the CFD model, forces and moments (disturbances) will be fed to the vehicle model. A MATLAB-Simulink program will be developed to simulate 2 degrees of freedom (2-dof) in a vehicle-driver model and investigate the effect of such disturbances on the driver-vehicle's lateral stability for various crosswind velocities and driver-vehicle parameters. The methodology is used in more than one reference: William, Oraby, and Metwally (2014), Habib (1996) and Habib (1997).

Hereinafter vehicle directional stability simulation procedure will be explained.

3.3.1. Vehicle Dynamic Model

Two degrees of freedom is the vehicle model considered for analyzing the vehicle lateral dynamics. First a vehicle model without disturbances was tested. Then, a vehicle-driver model without disturbances was tested. Finally, a vehicle-driver model with disturbances was tested. All simulations were done using MATLAB and Simulink programs.

3.3.1.1. Vehicle model without disturbances

The response of the vehicle in terms of yaw velocity Ω_z and lateral velocity V_y as a function of time can be determined by solving the differential equations 2.13 and 2.15 (Chapter 2), a state space model derived as follows:

Can be rearranged to:

$$\dot{V}_y = \left[-V_x - \frac{(2L_f C_{\alpha f} - 2L_r C_{\alpha r})}{mV_x} \right] \Omega_z - \left[\frac{2C_{\alpha f} - 2C_{\alpha r}}{mV_x} \right] V_y + \left[\frac{2C_{\alpha f}}{m} \right] \delta_f(t) \quad (3.1)$$

and

$$\dot{\Omega}_z = - \left[\frac{(2(L_f)^2 C_{\alpha f} + 2(L_r)^2 C_{\alpha r})}{I_z V_x} \right] \Omega_z - \left[\frac{2L_f C_{\alpha f} - 2L_r C_{\alpha r}}{I_z V_x} \right] V_y + \left[\frac{2L_f C_{\alpha f}}{I_z} \right] \delta_f(t) \quad (3.2)$$

Using state space representation:

Where

$$\begin{bmatrix} \dot{V}_y \\ \dot{\Omega}_z \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} V_y \\ \Omega_z \end{bmatrix} + \begin{bmatrix} B_{11} \\ B_{21} \end{bmatrix} \delta_f \quad (3.3)$$

Let;

$$A_{11} = - \left[\frac{2C_{\alpha f} - 2C_{\alpha r}}{mV_x} \right] \quad , \quad A_{12} = \left[-V_x - \frac{(2L_f C_{\alpha f} - 2L_r C_{\alpha r})}{mV_x} \right]$$

$$A_{21} = - \left[\frac{2L_f C_{\alpha f} - 2L_r C_{\alpha r}}{I_z V_x} \right] \quad , \quad A_{22} = - \left[\frac{(2L_f)^2 C_{\alpha f} + 2(L_r)^2 C_{\alpha r}}{I_z V_x} \right]$$

$$B_{11} = \left[\frac{2C_{\alpha f}}{m} \right] \quad , \quad B_{21} = \left[\frac{2L_f C_{\alpha f}}{I_z} \right]$$

and;

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; \quad D = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

where;

$$Z = \begin{bmatrix} V_y \\ \Omega_z \end{bmatrix} = C \begin{bmatrix} V_y \\ \Omega_z \end{bmatrix} + D \cdot \delta_f; \quad \text{And; } u = \delta_f$$

where;

$$y = Cz + Du$$

3.3.1.2. Vehicle Open loop simulation

To investigate vehicle characteristic, primary Open loop simulation contains the vehicle only without a driver as controller tested. Vehicle parameters in Table (7) are based on vehicle geometry and literature.

Table (7)

List of Vehicle parameters.

#	Parameter	Value
1	Vehicle weight (W)	19600 (N)
2	Vehicle length (L)	5.57 (m)
3	center of gravity distance from front wheel	$L/2$
4	Front tire Cornering Stiffness (C_{af})	30000 (N/rad)
5	Rear tire Cornering Stiffness (C_{ar})	30000 (N/rad)
6	Vehicle moment of inertia about Z axis (I_z)	500 (kg.m^2)
7	Steering wheel to tire angle ratio (Nsr)	20
8	Vehicle longitudinal velocity (V_x)	100 (km/h)

Putting all the parameters in a MATLAB and Simulink open loop model (Appendix D-1), using state-space equation (3.3) give the results in Figure (23), the three graph representing step steering angle input of 30 degree and the corresponding vehicle lateral and yaw velocities.

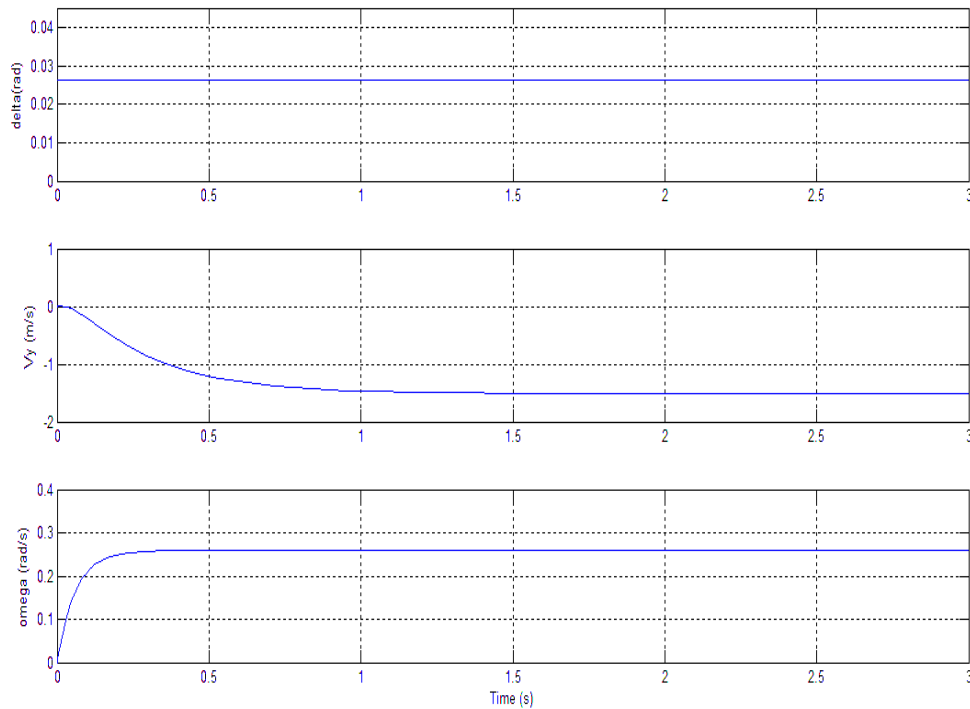


Figure (23)

Simulation result of open loop model representation.

3.3.2. Driver-Vehicle model

In the second phase, a close-loop model with a driver as a compensator is tested without disturbances. The aim is to study the influence of forward velocity, lead-time and reaction time on a vehicle's lateral responses in order to select driver parameter values to achieve good tracking performance.

Referring to Figure (13) in Chapter (2) which shows a block diagram of the compensatory tracking model of a closed driver-vehicle system, the driver will be represented by $H(s)$, where;

$$H(s) = K \frac{T_L s + 1}{T_R s + 1} \quad (2.19)$$

3.3.2.1. Driver-Vehicle model with Disturbance

A final model, with side wind as a source of disturbance tested. This created a side force and a yaw moment on the vehicle which effects the vehicle's lateral position and yaw angle during the steering. Figure (24) shows the block diagram of driver –vehicle feedback system with disturbance.

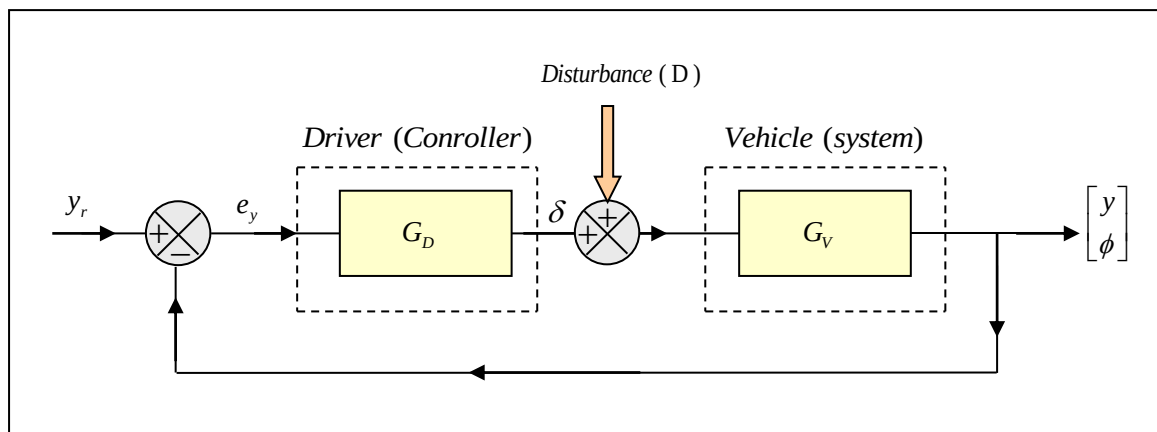


Figure (24)

Block diagram of Driver –Vehicle closed loop system with disturbances. Where (D) refer to disturbing forces, side force (F_y) and yawing moment (M_z). The effect of side wind disturbance was added to the vehicle feedback system.

Adding the disturbance changes to the governing equations, referring to equations (2.16) and (2.17) that represent the motion of vehicle under occurrence of external disturbances (such as crosswinds) for a vehicle in plane motion,

Can be rearranged:

$$\dot{V}_y = \left[-V_x - \frac{(2L_f C_{\alpha f} - 2L_r C_{\alpha r})}{mV_x} \right] \Omega_z - \left[\frac{2C_{\alpha f} - 2C_{\alpha r}}{mV_x} \right] V_y + \left[\frac{2C_{\alpha f}}{m} \right] \delta_f(t) + F_y \quad (3.4)$$

and

$$\dot{\Omega}_z = - \left[\frac{(2(L_f)^2 C_{\alpha f} + 2(L_r)^2 C_{\alpha r})}{I_z V_x} \right] \Omega_z - \left[\frac{2L_f C_{\alpha f} - 2L_r C_{\alpha r}}{I_z V_x} \right] V_y + \left[\frac{2L_f C_{\alpha f}}{I_z} \right] \delta_f(t) + M_z \quad (3.5)$$

Rewriting the above equations in state-space representation:

Where

$$\begin{bmatrix} \dot{V}_y \\ \dot{\Omega}_z \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} V_y \\ \Omega_z \end{bmatrix} + \begin{bmatrix} B_{11} & \frac{1}{m} & 0 \\ B_{21} & 0 & \frac{1}{I_z} \end{bmatrix} \cdot \begin{bmatrix} \delta_f \\ F_w \\ M_z \end{bmatrix} \quad (3.6)$$

let;

$$A_{11} = - \left[\frac{2C_{\alpha f} - 2C_{\alpha r}}{mV_x} \right] \quad , \quad A_{12} = \left[-V_x - \frac{(2L_f C_{\alpha f} - 2L_r C_{\alpha r})}{mV_x} \right]$$

$$A_{21} = - \left[\frac{2L_f C_{\alpha f} - 2L_r C_{\alpha r}}{I_z V_x} \right] \quad , \quad A_{22} = - \left[\frac{(2(L_f)^2 C_{\alpha f} + 2(L_r)^2 C_{\alpha r})}{I_z V_x} \right]$$

and;

$$B_{11} = \left[\frac{2C_{\alpha f}}{m} \right] \quad , \quad B_{21} = \left[\frac{2L_f C_{\alpha f}}{I_z} \right]$$

and;

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; \quad D = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}; \quad z = \begin{bmatrix} V_y \\ \Omega_z \end{bmatrix} \quad \text{And}; \quad u = \begin{bmatrix} \delta_f \\ F_w \\ M_z \end{bmatrix}$$

where;

$$y = C \begin{bmatrix} V_y \\ \Omega_z \end{bmatrix} + D \cdot \begin{bmatrix} \delta_f \\ F_w \\ M_z \end{bmatrix} ;$$

where;

$$y = Cz + Du$$

Based on parameters in Table (8) and space-state equations (3.6) a MATLAB and Simulink closed-loop model representing driver-vehicle with disturbance (Appendix D-2). Assumed values of M_z and F_s based on the investigation results of aerodynamic forces used to test the model, see Figure (25).

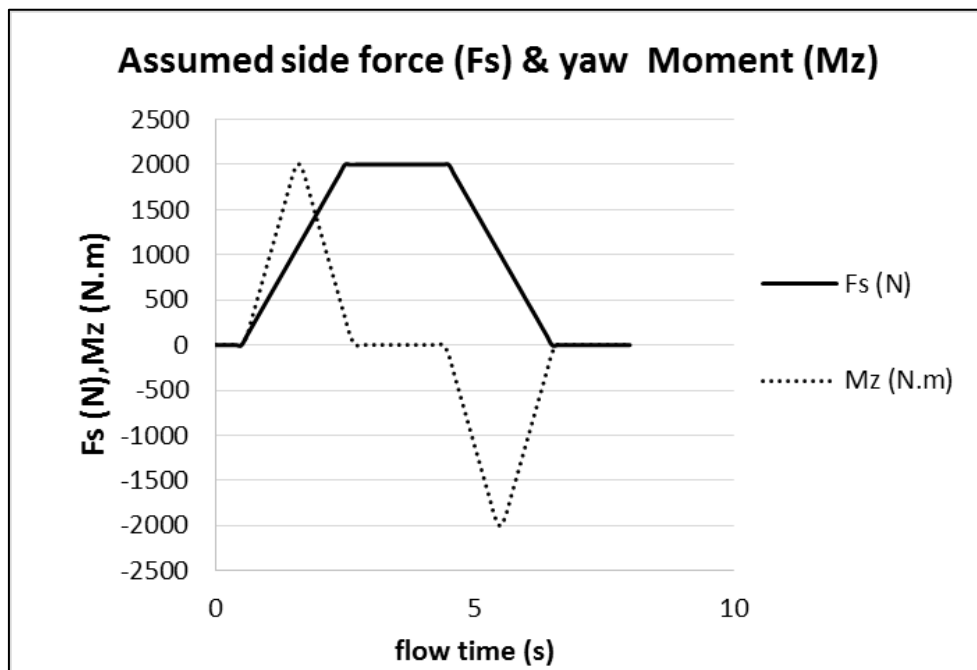


Figure (25)

Assumed side force (F_s) & yaw Moment (M_z)

The test results of forces assumed in Figure (25) are shown in Figure (26), and reveals that yaw moment effect is more than side force. This result is expected according to the literature review (Hucho and Sovran 1993).

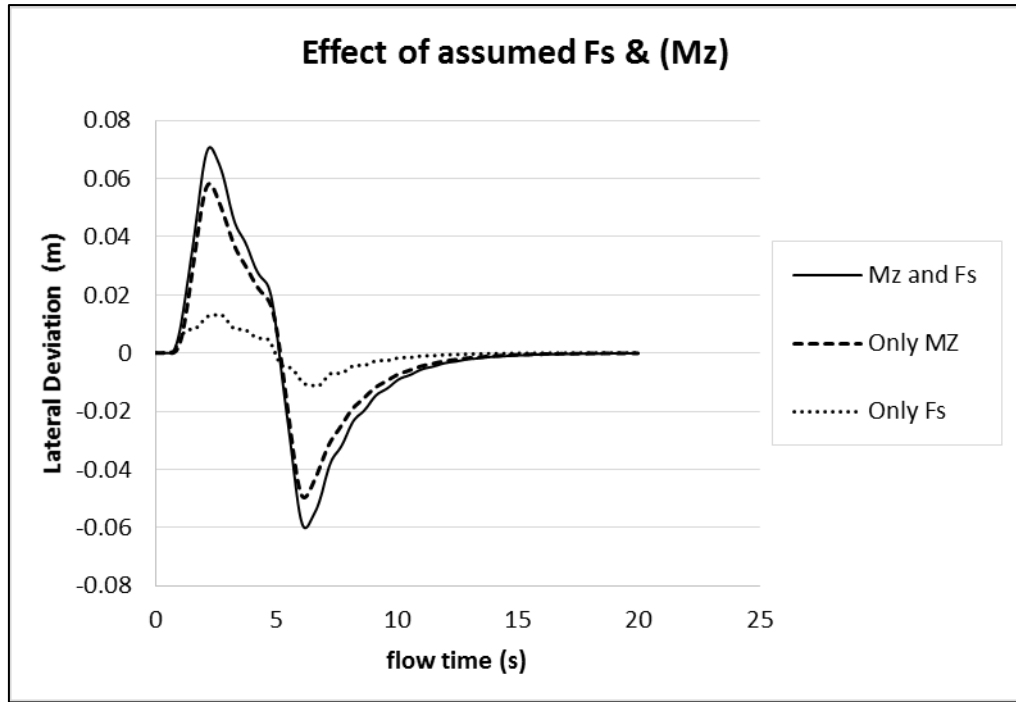


Figure (26)

Effect of assumed Fs & (Mz) on lateral Deviation.

The model then used the data of aerodynamic forces thus resulted from Ansys Fluent, and the data is saved on data sheet with format (Microsoft Excel) as timetables, then imported to MATLAB in a column vector format. Any missing values were replaced with a zero value. Imported data is named according the names titled in the Simulink model.

3.3.2.2. The model Eigenvalue

Eigen value is used as indicator of system stability. Figure (27) shows a negative exponential that represents stable/converging solutions.

To investigate the effects of different wind velocity, verity of crosswind velocity of (10, 20 and 30 m/s) at 90° angle (the normal wind found to give higher forces values), is tested in the same vehicle velocity 27 m/s. These wind velocities represent extreme wind conditions such as storms. The causeway speed is 100 km/h (27.7m/s), to investigate the effect of vehicle velocity 80 km/h (22.22 m/s),

120 km/h 33.33 m/s velocities are tested, which represent (+ and -) 20% of the causeway speed. A list of all conditions tested can be found in Table (8).

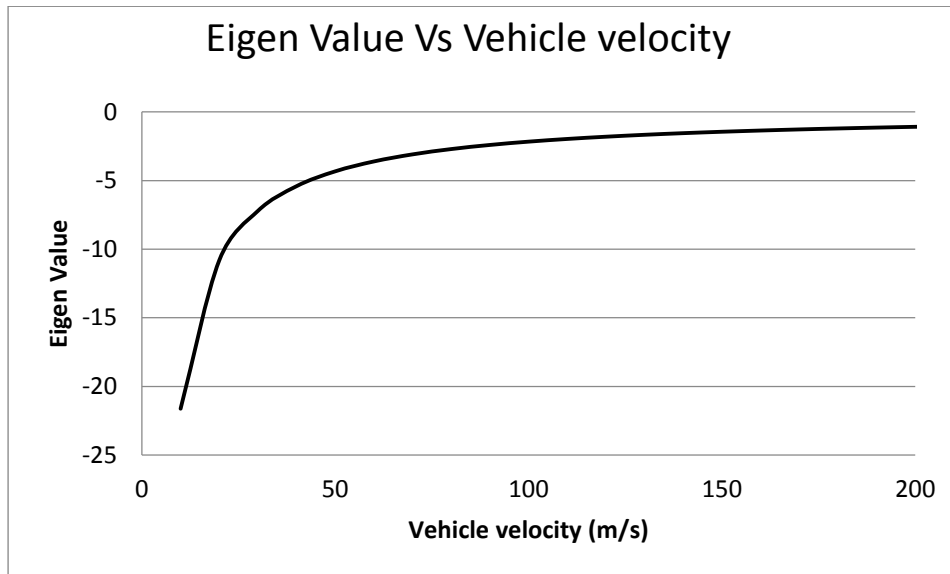


Figure (27)

Eigen value Vs Vehicle velocity.

Table (8)

List of Vehicle velocity and wind velocity tested.

#	Vehicle velocity (vehicle zone translation in y-axis)	Wind velocity (m/s)	Wind direction (Compared to vehicle travel direction)
1	97.2 km/hr. (27 m/s)	20	90°
		30	
2	80 km/hr. (22.22 m/s)	30	
3	120 km/hr. (33.33 m/s)	30	

The results are then presented as tables and graphs of lateral deviation, yaw angel response and error from desired values.

Chapter 4

Results and Discussion

Chapter 4

Results and discussion

4.1. Aerodynamic Simulation results

4.1.1. Model validation

4.1.1.1. Single model geometry validation

Similar to the simulation of Corin et al. (2008), a test for isolated vehicle models was conducted. Experimental and computational pressure coefficients (C_p) along PARAD1 model in figure (28-a), compared to figure (28-b) from Corin et al. (2008) which includes experimentally and CFD data for the same PARAD1 model.

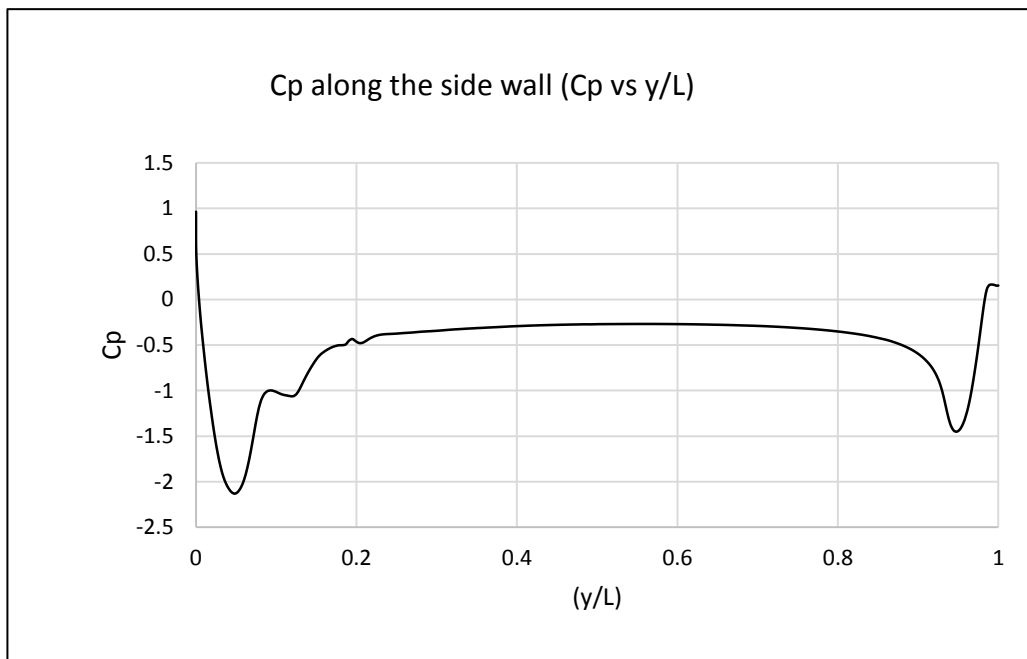


Figure (28-a)

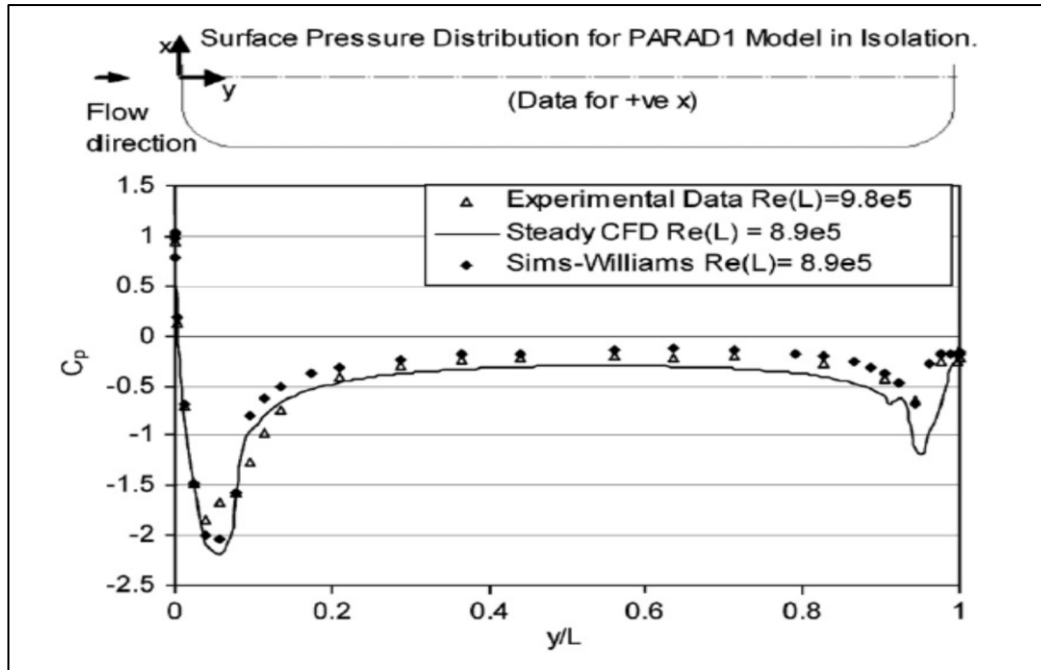


Figure (28-b)

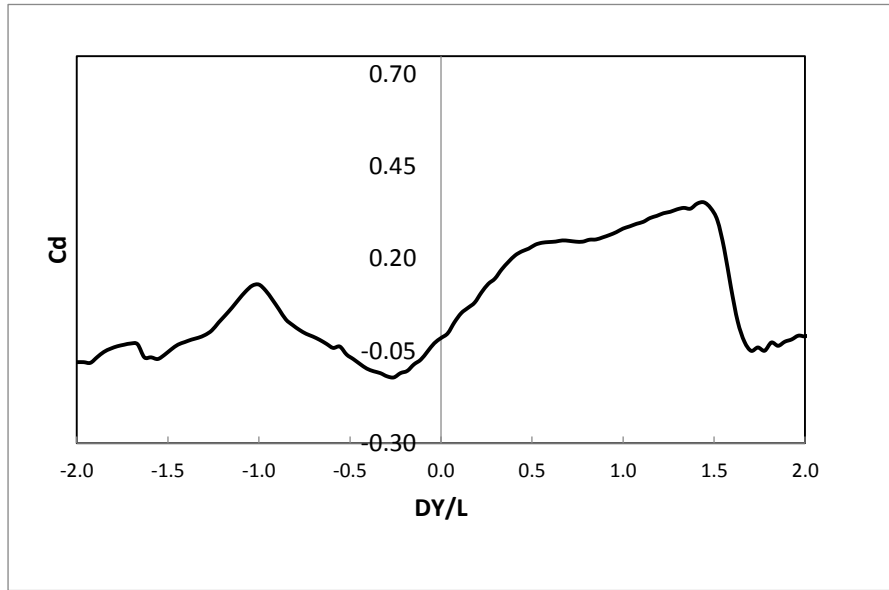
Pressure distribution for PARAD1 results. (28-a) This work, and (28-b) Experimental and CFD from Corin et al. (2008).

The comparison shows a similarity in results validating the vehicle geometry used.

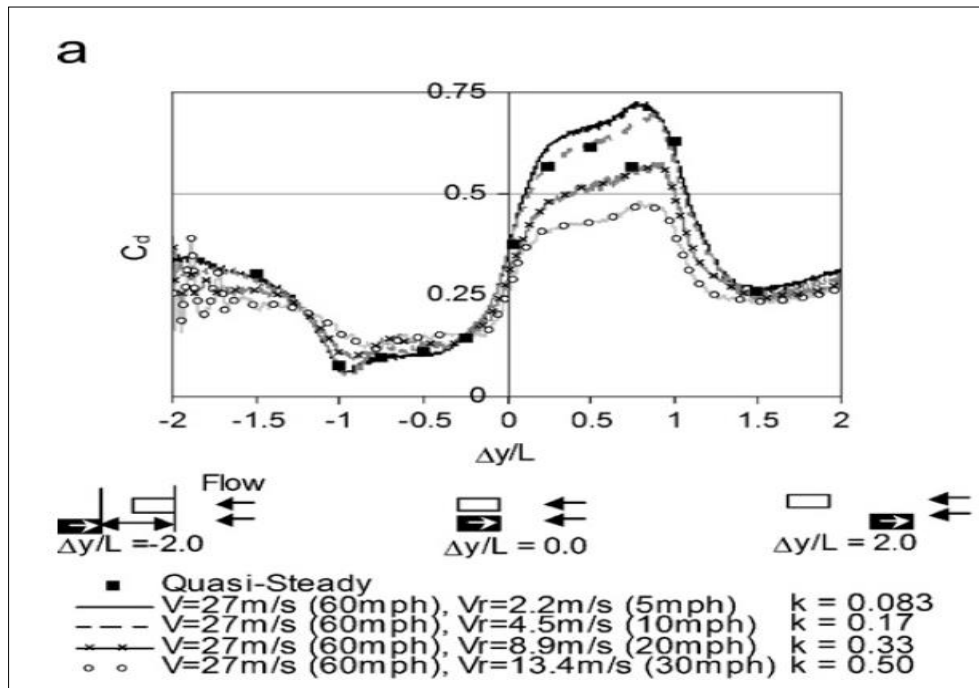
4.1.1.2. Validation of the unsteady solver

Figure (29) show C_d comparison between replicated simulation result and results from Corin et al. (2008). Pressure contour of the two vehicles while takeover replicated simulation presented and compared in figure (30) at relative velocity $V_r = 13.4$ m/s.

Both C_d results and pressure contours show similarity and validate the unsteady solver.



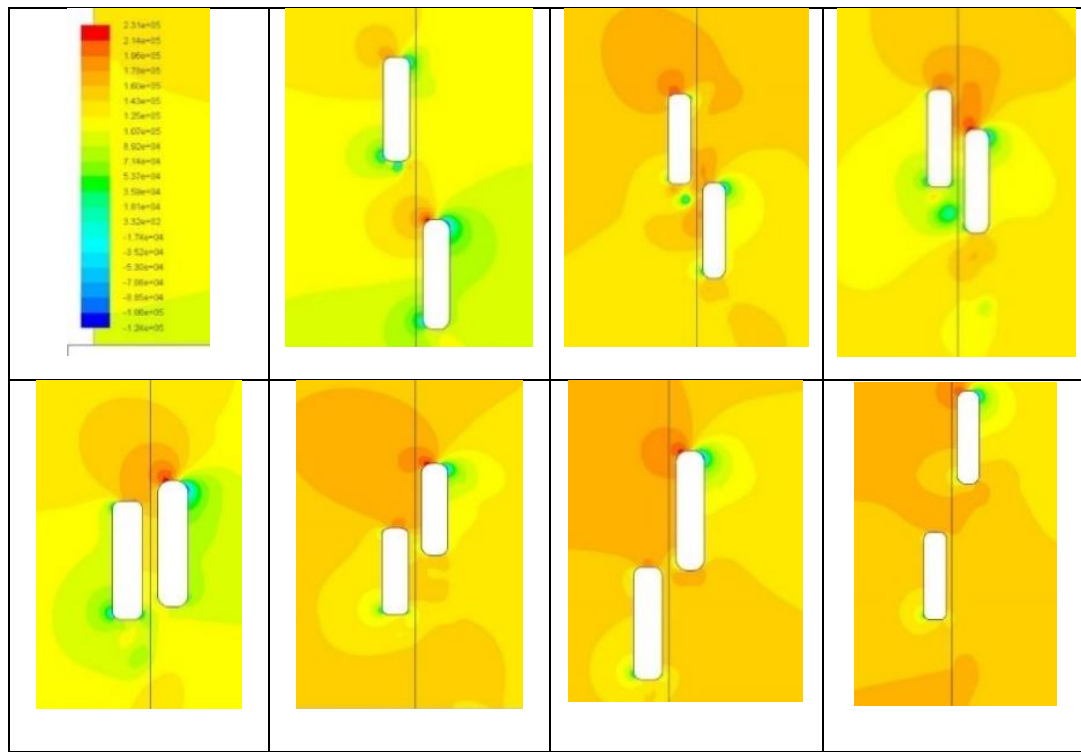
((a))



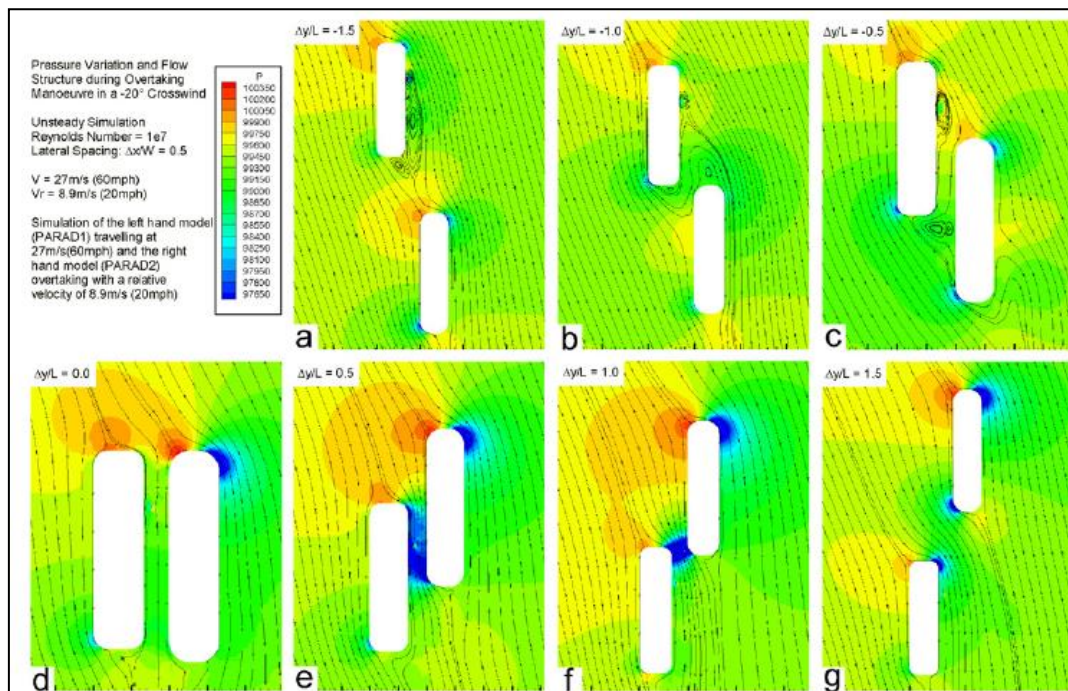
((b))

Figure (29)

Sliding mesh results C_d vs $\Delta Y/L$ at V_r 13.4 m/s, from a) present work, b)
Corin et al. (2008)



(a)



(b)

Figure (30)

Pressure fields for overtaking maneuver in yaw angle = -20 degree (a) replicated simulation, and (b) from Corin et al. (2008).

4.1.2. Aerodynamic Model simulation results and discussion

4.1.2.1 Effect of time steps

To find the effect of time steps, a model was tested under 30 m/s cross wind at 90 degree with (180, 360, 720 time steps) or step size of (0.064, 0.032, and 0.016 s), where total time is the same 11.52 s, a smaller time step gave a more precise result, but took more time for calculation. Comparing results of side force in Figure (31) and drag in Figure (32), the model shows more frequency in 720 steps results, a smoother curve in 180 steps results, and 360 steps in between. Values are almost the same for all step sizes in side force, where drag force show more difference, revealing that side forces are 10 times higher than drag forces.

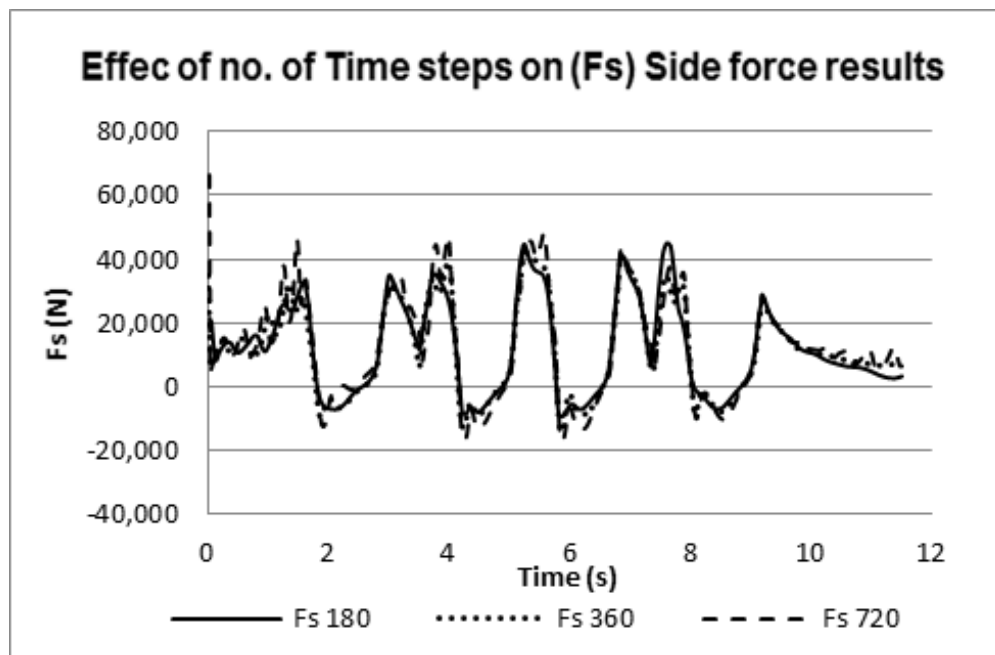


Figure (31)

Effect of no. of time steps on side force results, $V_v=27\text{m/s}$, $V_w=30\text{m/s}$,

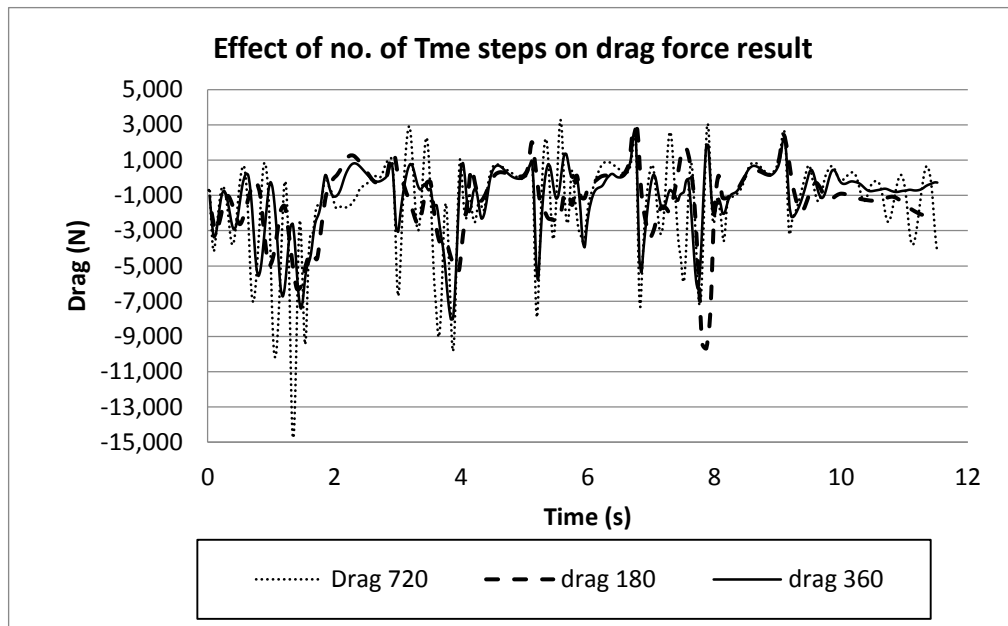


Figure (32)

Effect of no. of time steps on drag force results, $V_v=27\text{m/s}$, $V_w=30\text{m/s}$.

4.1.2.2. Wind velocity contour cross the bridge

From Figure (33), velocity contours show wind velocity and direction change throw the lanes along the bridge, when the upstream velocity is 27m/s , it is reaching 98 m/s in the mid open. It also calculates zero directly behind the sails and negative after the sails show some vortices.

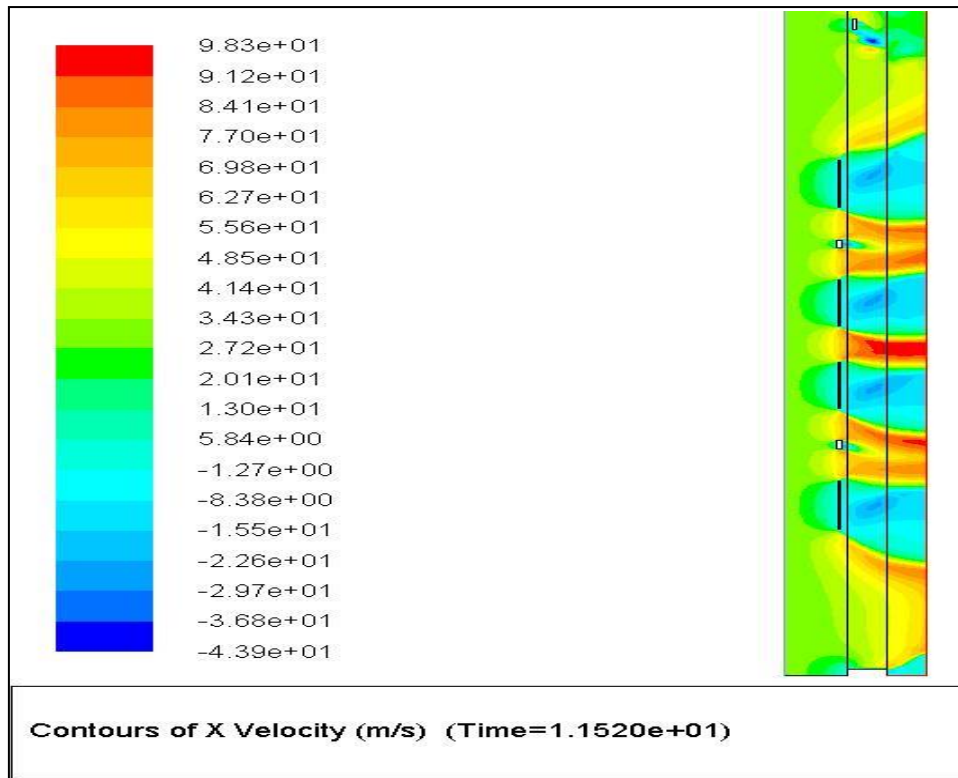


Figure (33).

Velocity contours of wind in x direction crossing the bridge with $V_w = 30\text{m/s}$ the bridge.

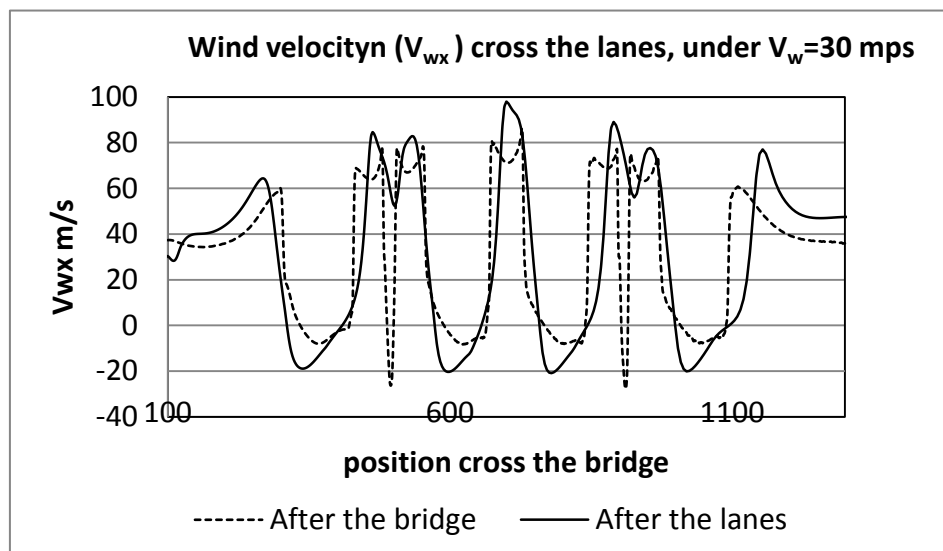


Figure (34)

Velocity of wind in x-direction in 1st lane (adjacent bridge wall) and 3rd lane (2 lanes from bridge wall) cross the bridge.

Similar notice of wind velocity variations in Figure (34), where x-direction velocity is in the first lane after the sails directly showed less value in peaks and more variant in value whereas after the lanes the velocity is more in peaks and less variant. A negative pulse due the column between the sails can observed.

4.1.2.3. Effect of wind velocity

Load results of different wind velocities in Figures (35) to (36); wind velocity V_w of (20 m/s and 30 m/s) at 90 degree a is tested. At $V_v = 27$ m/s, increase in V_w result increase in loads.

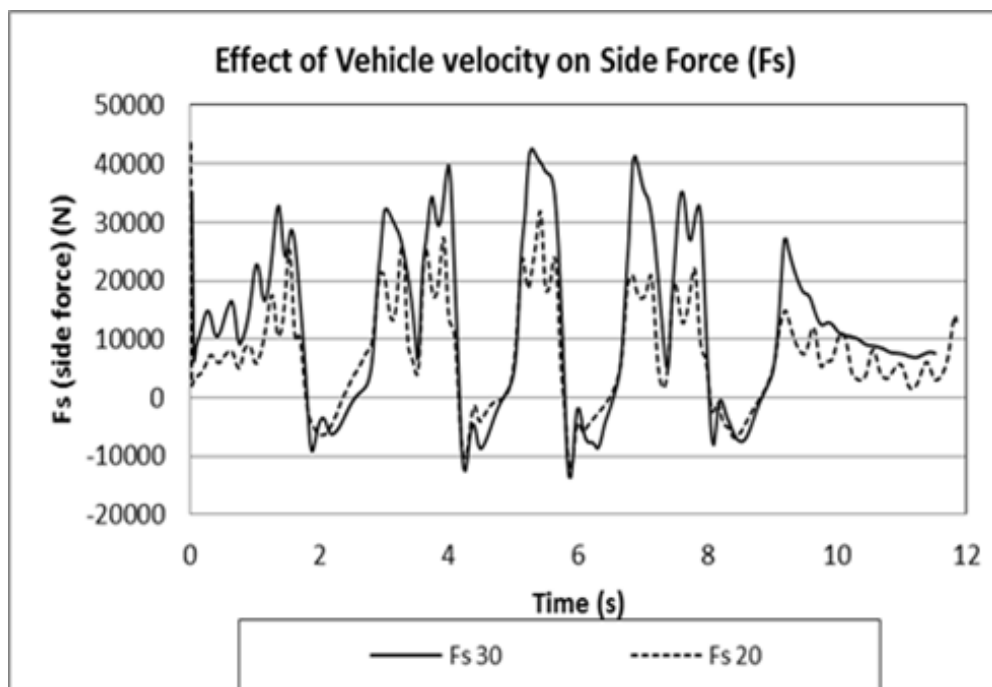


Figure (35)

Effect of wind velocity on side force results, at $V_v = 27$ m/s.

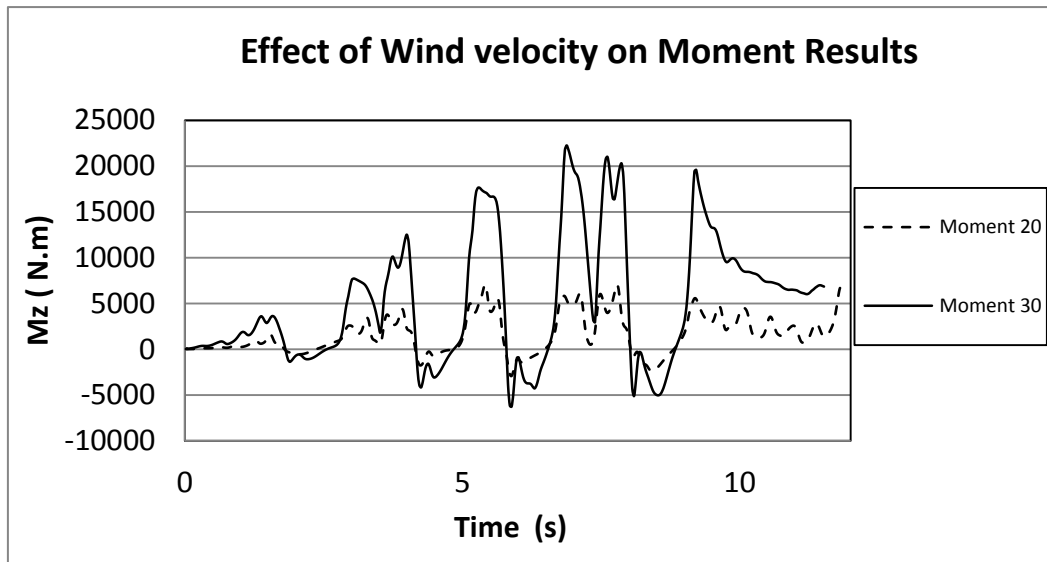


Figure (36)

Effect of wind velocity on moment results, at $V_v=27$ m/s.

4.1.2.4. Effect of wind attack angle

Crosswinds at 30 m/s, with attack angles at 45° , 60° , and 90° were tested at vehicle velocity of 27 m/s, the effect of attack angle on wind velocity profile is clear in Figure (37).

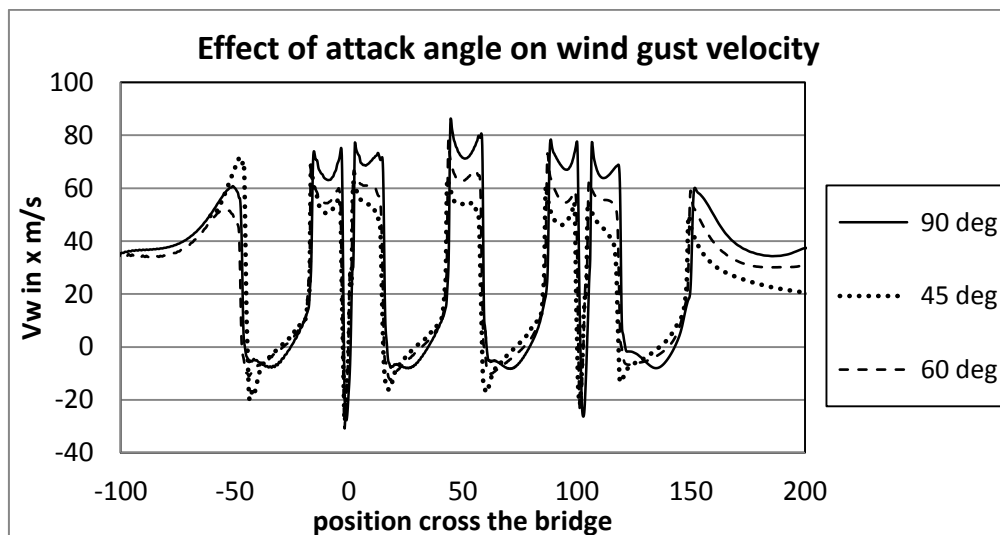


Figure (37)

The effect of attack angle on wind velocity (at $V_w=30$ m/s, $V_v=27$ m/s).

More inclined angle result in reduced wind velocity, and in most peaks, Figure (38) is a comparison between different angle results.

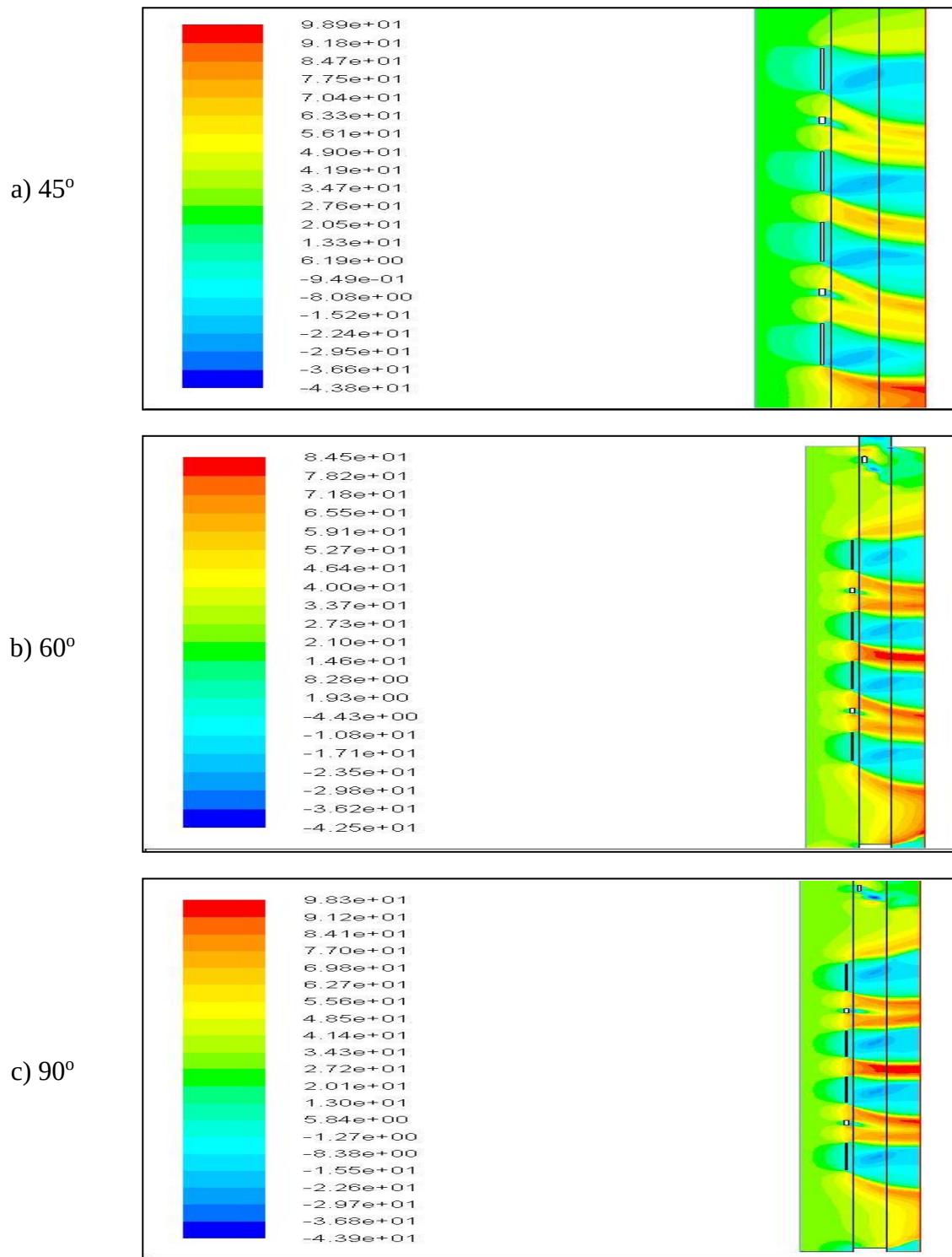


Figure (38)

Effect of attack angel wind contour of x- velocity, angle a) 45°, b) 60°, and c) 90°, at $V_w=30$ m/s.

On the other hand, generated loads reduced by the inclination are observed in the moment Figure (39) which is more than lateral force generated in Figure (40)

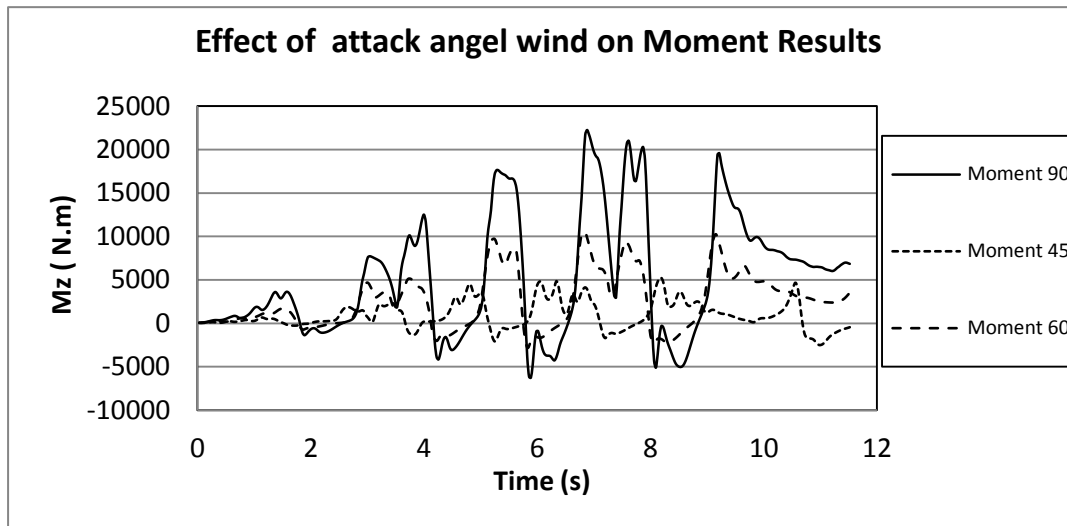


Figure (39)

Effect of attack angel wind on moment results, at $V_w=30$ m/s, $V_v=27$ m/s.

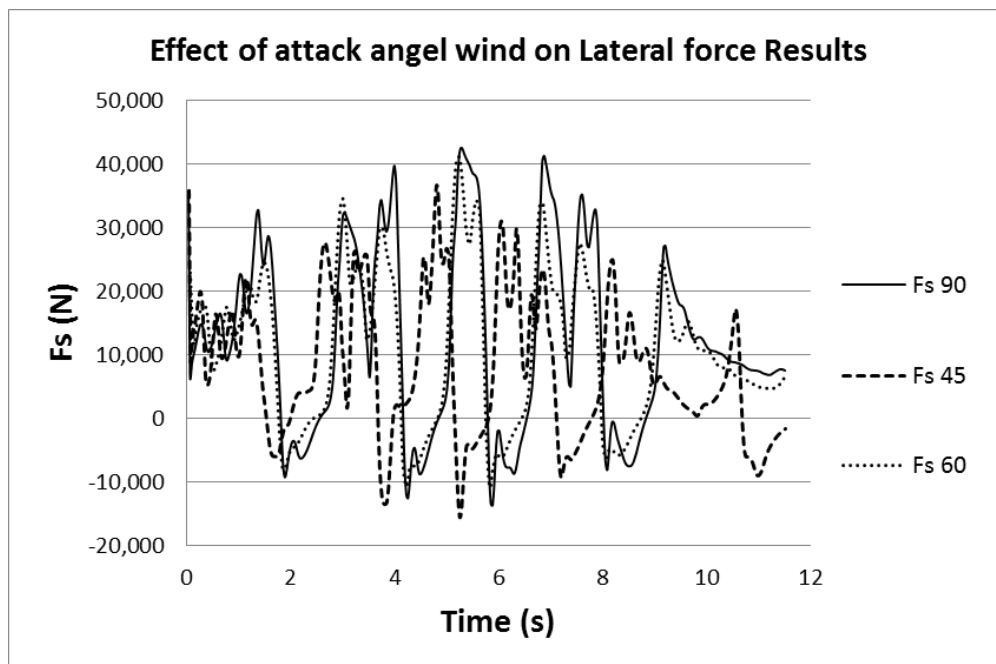


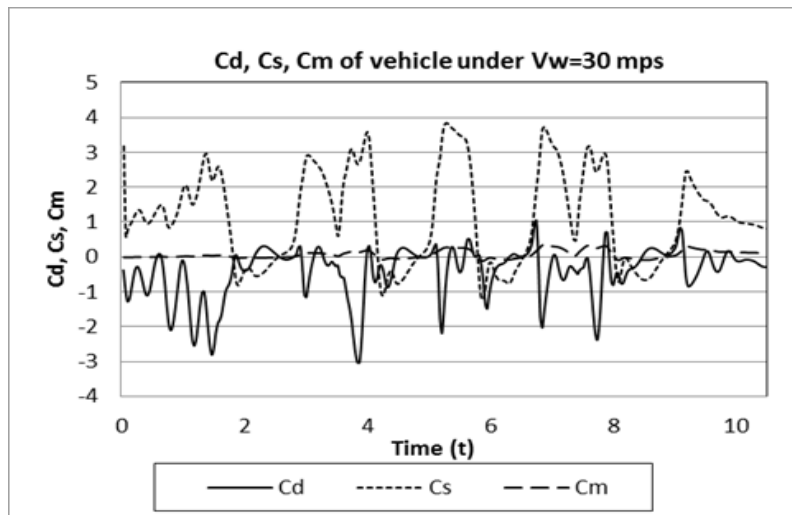
Figure (40)

Effect of wind attack angel on lateral force results, at $V_w=30$ m/s, $V_v=27$ m/s.

4.1.2.5. Sample results

Results of vehicle velocity $V_v=27$ m/s, cross wind velocity $V_w= 30$ m/s at 90° presented. Dimensionless coefficients (C_d , C_l and C_m) results Figure (41), are given from the software. The software use the force to calculate the coefficient, forces and moments are calculated using coefficients. Result are shown in figure (42).

Figure (41)



Drag, side force and moment coefficients of vehicle crossing the bridge at $V_v=27$ m/s, in under $V_w=30$ m/s.

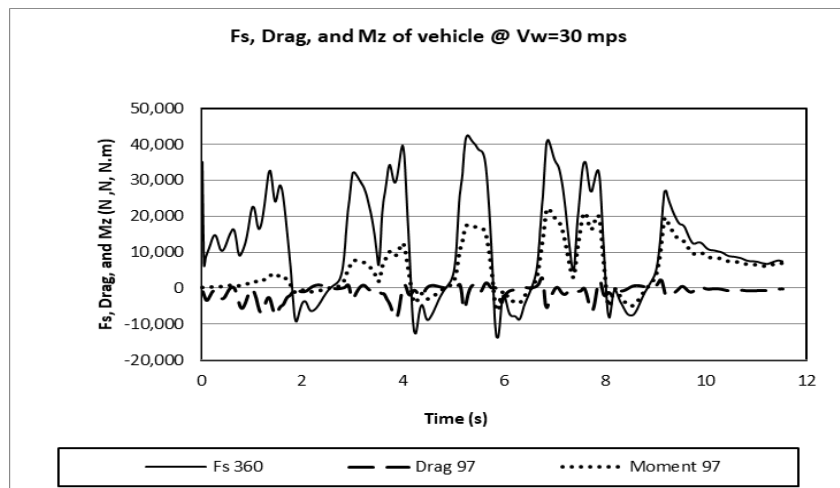


Figure (42)

Drag, side forces and moment affecting the vehicle crossing the bridge at $V_v=27$ m/s, in under $V_w=30$ m/s.

4.1.2.6. Effect of vehicle velocity

Load results of different vehicle velocities in Figures (43) and (44); vehicle velocity of (22.22 m/s, 27 m/s and 33.33 m/s) is tested. At $V_w = 30$ m/s, 90 degree angles are presented. Increase in V_v results in an increase in lateral (side) loads and more observed moment increase.

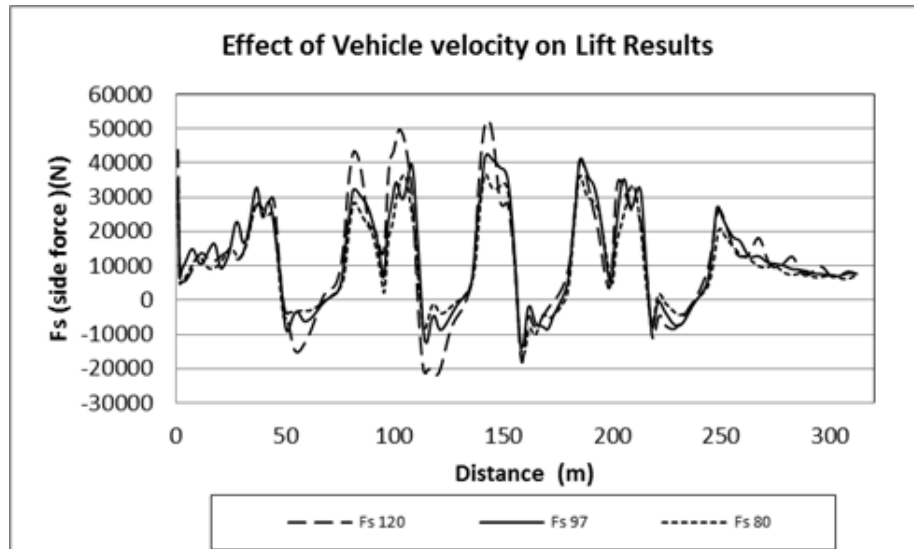


Figure (43)

Effect of Vehicle velocity on side force results, at $V_w = 30$ m/s.

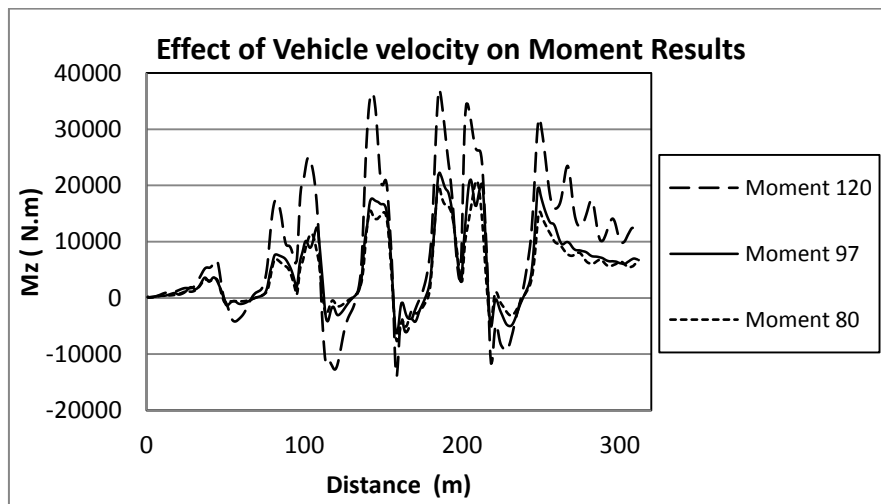


Figure (44)

Effect of Vehicle velocity on Moment results, at $V_v = 27$ m/s.

4.2. Aerodynamic Simulation results Discussions

Computational fluid dynamics (CFD) and a sliding mesh technique are methods successfully developed and applied to the study of aerodynamic forces on vehicles overtaking bridges in crosswind. A2-d simplified representation of the vehicle and bridge focused on the effect of wind velocity and vehicle velocity. Validation for model and geometrically successful matches case seen in previous studies.

The investigation highlights the effect of wind velocity and vehicle velocity on the Aerodynamic forces generated on the vehicle.

The wind a cross the bridge is found to be increase in velocity 3 times more than the free stream in the opining with large value and direction variations. Wind direction (attack angle) may change wind contour after the bridge sails. Maximum values found when the wind is perpendicular to the bridge and forces finding have the same pattern. Wind results patterns and values are in match with previous studies like Charuvisit, S. Kimura, K. Fujino, Y. (2004a).

Moment is affected more than side force by vehicle velocity (V_v) changes; increasing V_v to 120km/h gave double the value in 97 km/hr., results match's previous studies in patterns and values like Rocchi et al. (2012). Repeated pattern in wind and forces is generated compared to previous studies was found and that is because they handle single tower wake, whereas in this work 6 wakes with special arrangement.

4.3. Vehicle lateral dynamic stability results

4.3.1. Effect of driver parameters on vehicle response

In this section, simulation of driver-vehicle system tracking is presented using MATLAB/SIMULINK program. The purpose of this section is to study the influence of forward velocity, lead-time and reaction time on vehicle lateral responses. The obtained results are discussed, in order to select the best parameters to achieve good tracking performance.

4.3.2. Effect of Lead Time (TL) and Reaction Time (TR) on the lateral response

As shown in Figures (45 and 46), the driver characteristics play a significant role in the vehicle response. From the figures, we conclude that the best driver conditions are achieved when the lead-time is maximum and the reaction time is at a minimum.

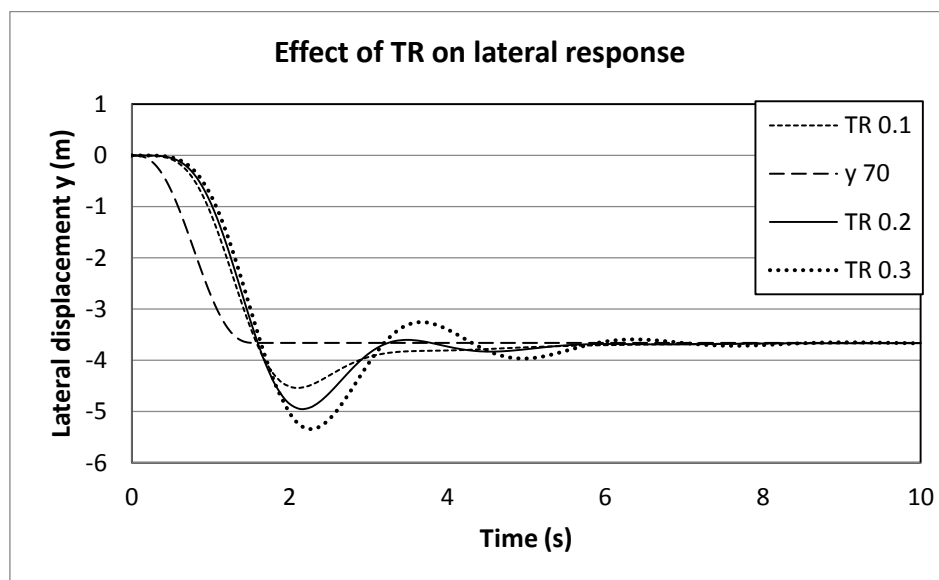


Figure (45)

Effect of Reaction Time TR on the lateral response

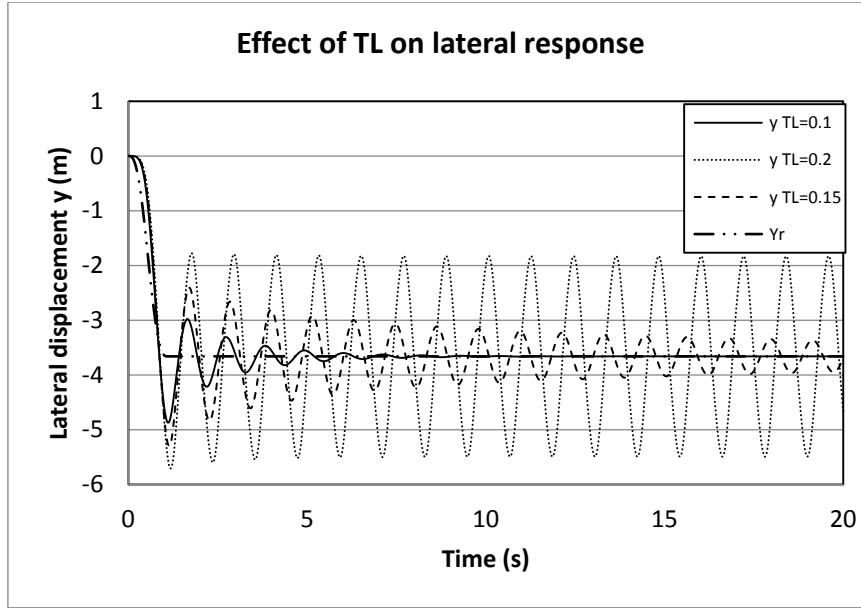


Figure (46)

Effect of Lead Time (TL) on the lateral response

4.3.3. Effect of the lateral position gain (K) on vehicle stability:

In the following Figure(47), the effect of the lateral position gain (K) on the vehicle stability at a constant forward velocity (100 km/h), lead-time =1.5 sec, and reaction time=0.15 sec is presented.

From Figure (47-c), at lateral position gain (K) = 0.5, unstable conditions are obtained. In Figure (47-b) K = 0.1, limit stability conditions are obtained. While in Figure (47-a) K = 0.05, the stable condition is shown. From these results, the system stability domain may be obtained numerically at various forward velocities.

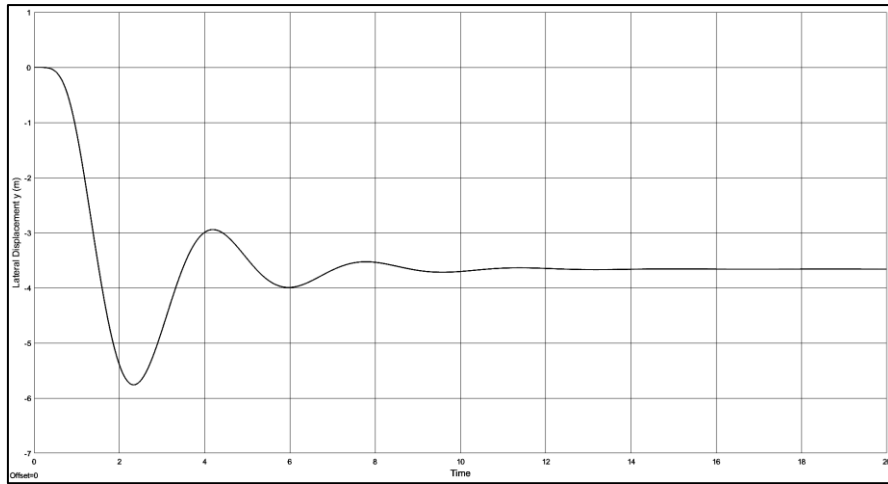


Figure (47- a) $K = 0.01$.

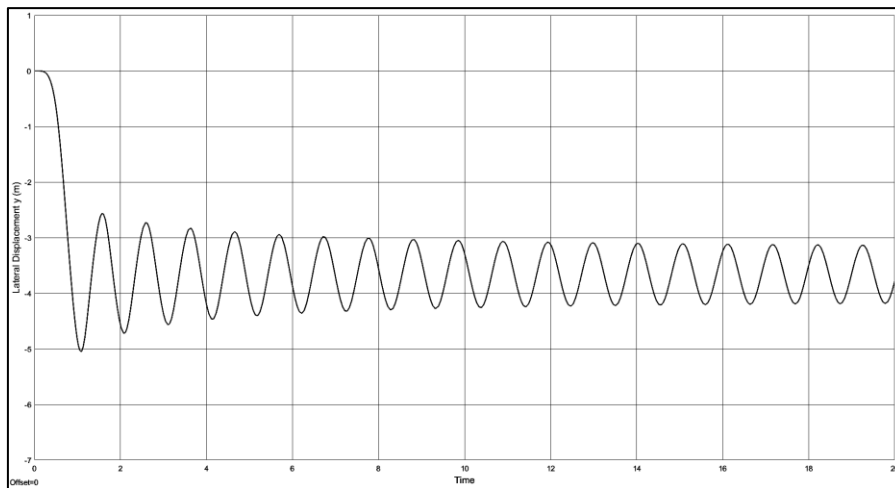


Figure (47-b) $K = 0.1$

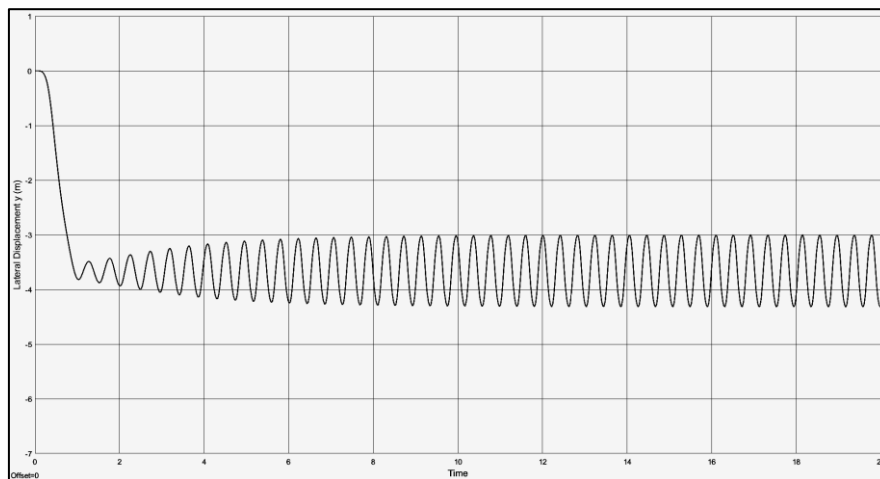


Figure (47-c) $K = 0.5$

Figure (47)

Effect of lateral position gain (K) on the vehicle stability.

After performing the forgoing steps in Figure (47), the following results in Figure (60), are obtained.

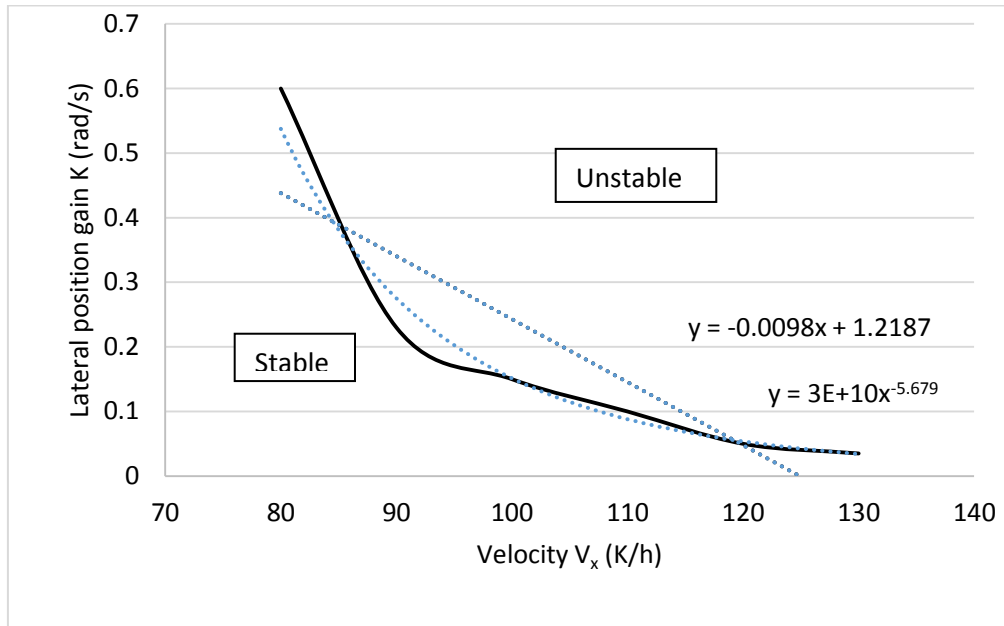


Figure (48)

Stability domain of vehicle driver system.

Figure (48) shows the stability domain, where the area under the curve is stable, and the area above the curve is unstable. Obviously, the forward velocity V_x and the lateral position gain K affect the vehicle's stability significantly.

Therefore, in a case of aggressive steering at a high forward velocity may lead to an unstable situation.

From Figure (60), a relationship between the lateral position gain and the forward velocity V_x is concluded in the following power equation:

$$K = 3E+10(V_x)^{-5.679}$$

Alternatively, following the linear approximation:

$$K = -0.0098(V_x) + 1.2187$$

The actual operating velocity range is (30-120) km/h, in which the percentage error is < 2 percentage.

4.3.4. Effect of forward velocity on the lateral position:

In the following Figures(49,50), the effect of a vehicle's forward velocity on the vehicle's lateral position at lead-time =2sec, reaction time=0.2 sec and lateral position gain =0.02 rad/s, is revealed in th investigation results.

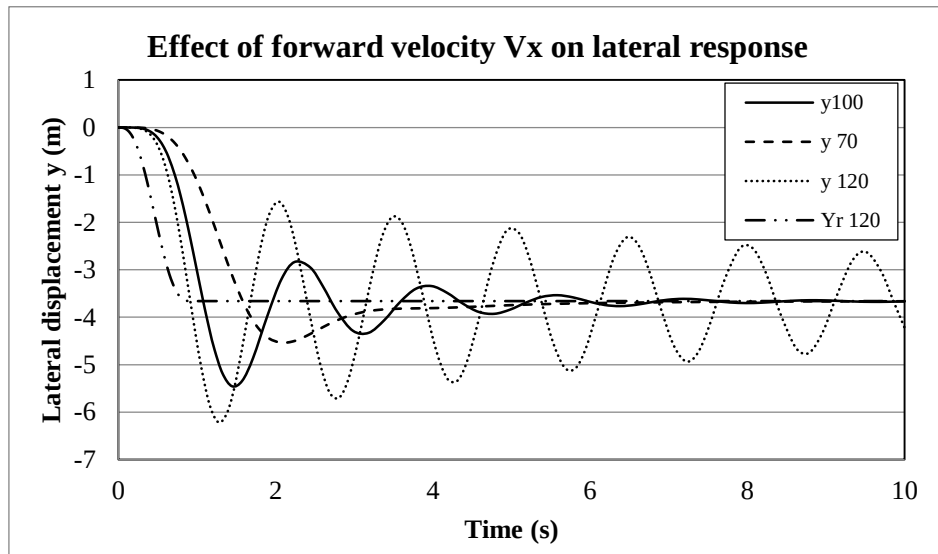


Figure (49)

Effect of forward velocity v_x on lateral response.

Figure (49 and 50) show the effect of the vehicle forward velocity V_x on vehicle lateral response. It is obvious that, when the velocity of the vehicle increases the percentage of overshoot increases and the response becomes more oscillatory. Therefore, as the velocity increases the vehicle will be more difficult to control

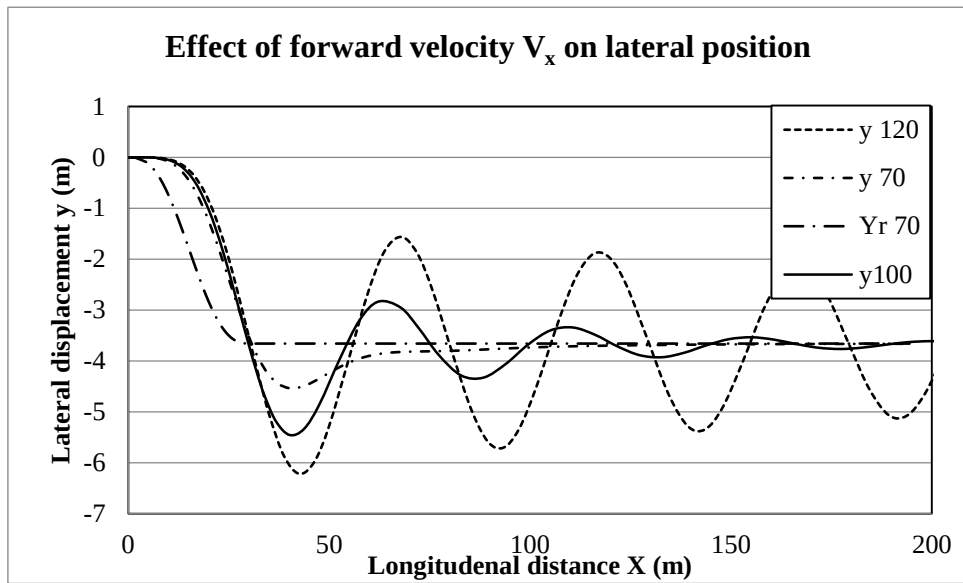


Figure (50)

Effect of forward velocity v_x on position

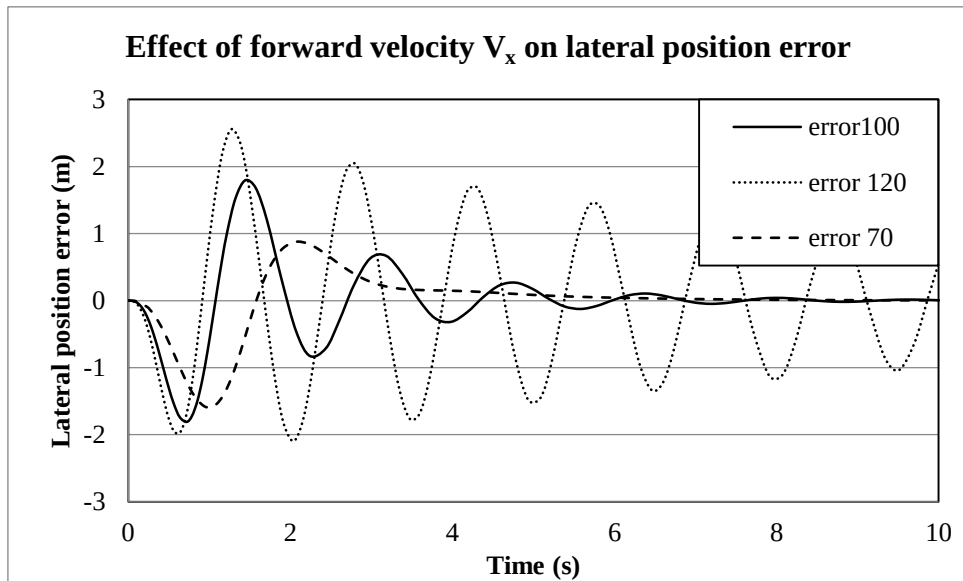


Figure (51)

Effect of forward velocity V_x on the lateral position error

Figure (51) shows the difference between the desired path and the lateral displacement in time domain.

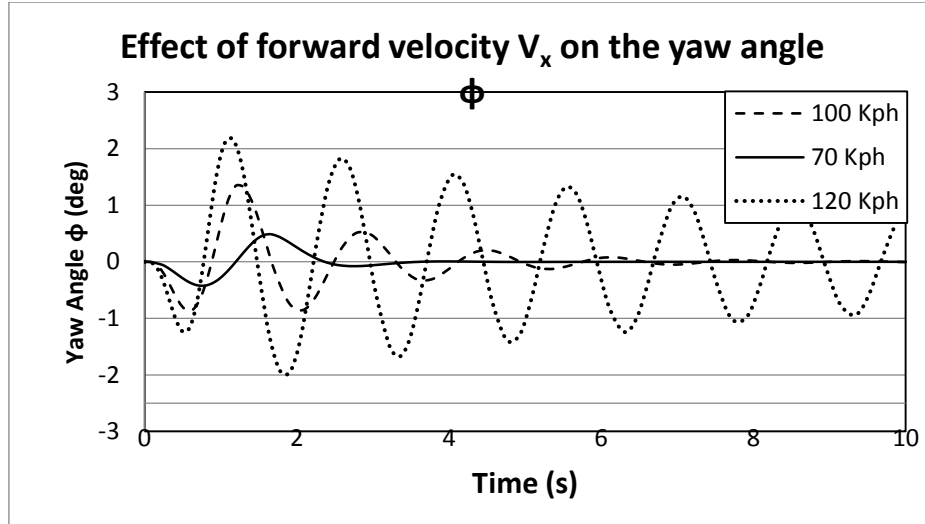


Figure (52)

Effect of forward velocity V_x on the yaw angle ϕ .

From Figure (52), the yaw angle increases as the vehicle velocity increases.

4.3.6. Results of simulation with disturbing forces

Lateral displacement, position and yaw rate result of ($V_x=27$ m/s and V_w 20 m/s at 90°) in tests are shown in Figures (53 and 54).

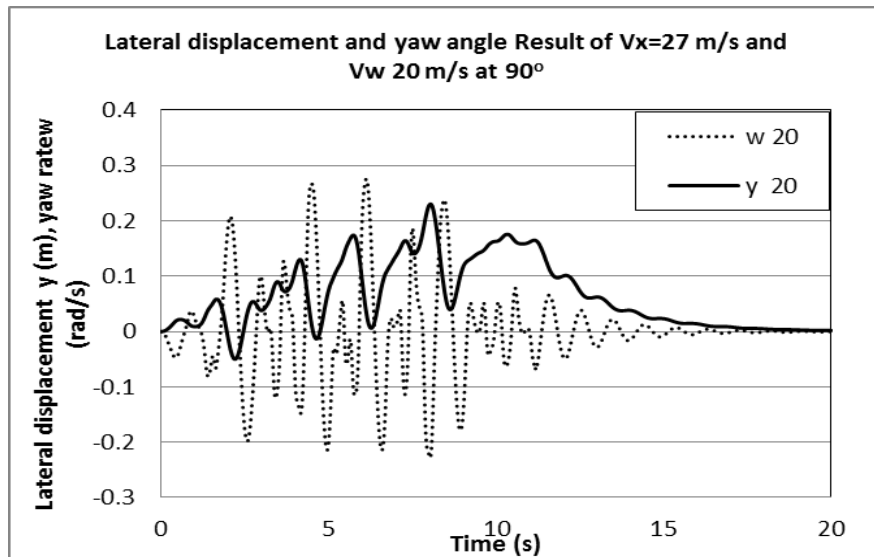


Figure (53)

Lateral displacement and yaw rate result of $V_x=27$ m/s and $V_w=20$ m/s at 90° .

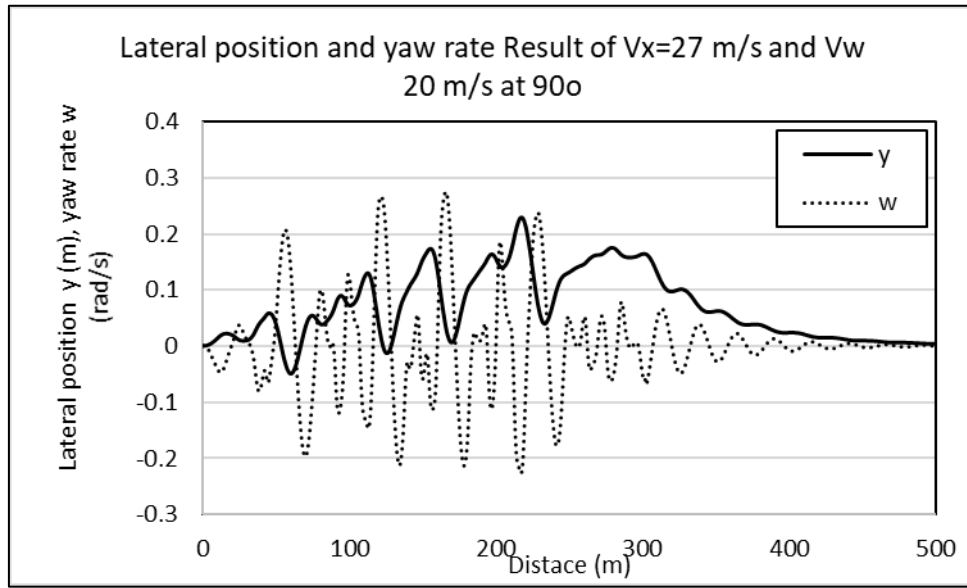


Figure (54)

Lateral position and yaw angle result of $V_x=27$ m/s and V_w 20 m/s at 90° .

Lateral displacement, position and yaw angle result of ($V_x=27$ m/s and V_w 30 m/s at 90°) test are shown in figures (55 and 56).

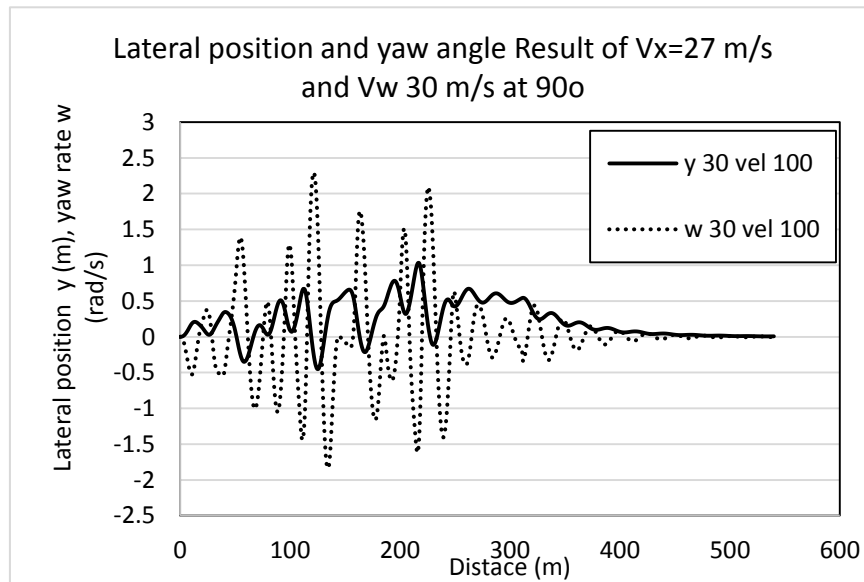


Figure (55)

Lateral position and yaw angle result of $V_x=27$ m/s and V_w 30 m/s at 90° .

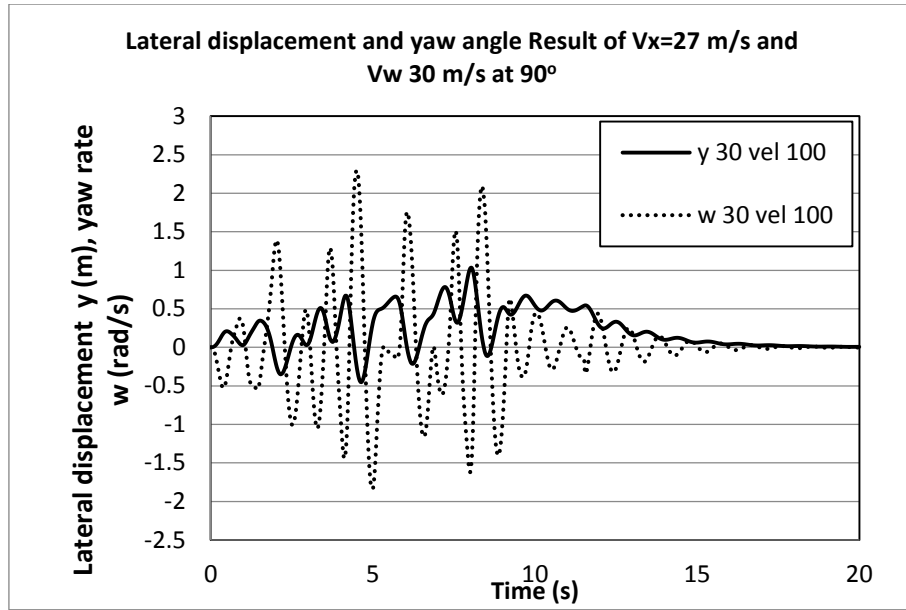


Figure (56)

Lateral displacement and yaw rate result of $V_x=27$ m/s and V_w 30 m/s at 90° .

Lateral displacement, position and yaw angle result of ($V_x = 22.22$ m/s and V_w 30 m/s at 90°) test are shown in figures (57 and 58).

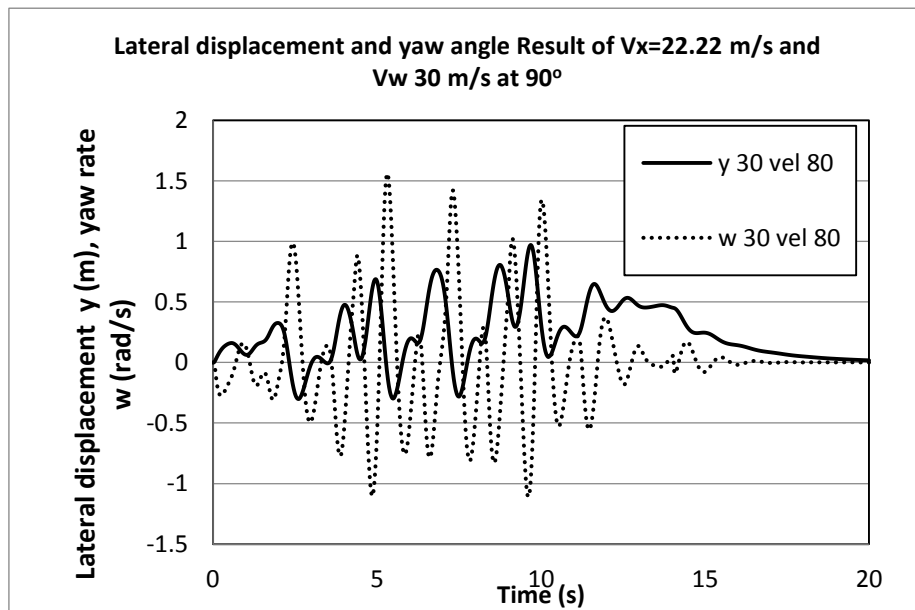


Figure (57)

Lateral displacement and yaw angle result of $V_x=22.22$ m/s and V_w 30 m/s at 90° .

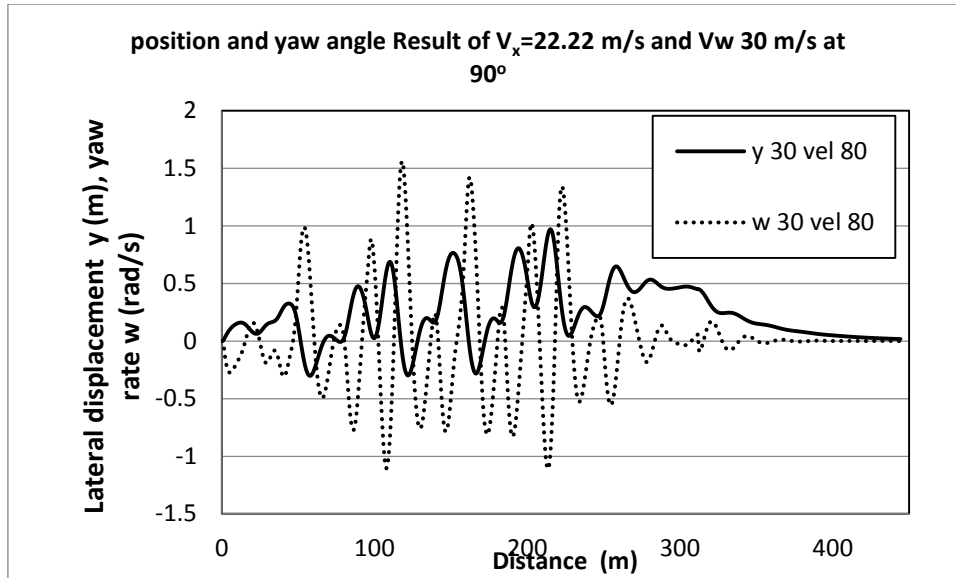


Figure (58)

Position and yaw angle result of $V_x=22.22$ m/s and V_w 30 m/s at 90° .

Lateral displacement, position and yaw angle result of ($V_x=33.33$ m/s and V_w 30 m/s at 90° test are shown in figure (59).

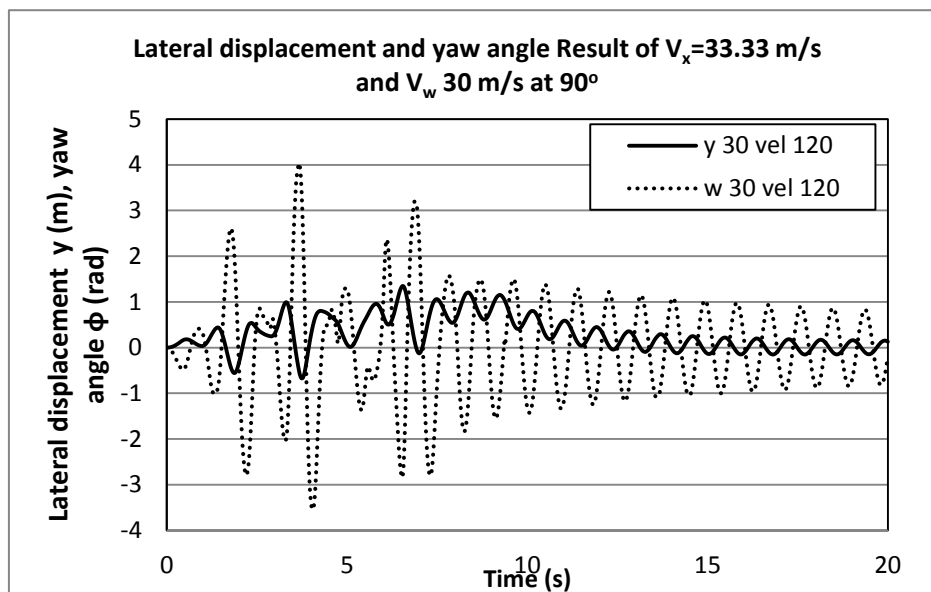


Figure (59)

Lateral displacement and yaw angle result of $V_x=33.33$ m/s and V_w 30 m/s at 90° .

4.3.7. Effect of wind velocity (V_w) discussion

A comparison between lateral displacement between $V_w=30$ m/s and $V_x=20$ m/s at 90° , $V_v = 30$ m/s, is shown in Figure (60) shows that patterns are the same for both with maximum absolute peak value at 124 and 217 m. Value increased almost 5 times by increasing wind velocity to 50%.

A comparison between yaw angle results between $V_w=30$ m/s and $V_x=20$ m/s at 90° , $V_v = 30$ m/s, is shown in Figures (61). Patterns are the same for both, with maximum absolute peak value at 125 and 225 (m), value increased almost 10 times by increasing wind velocity to 50%.

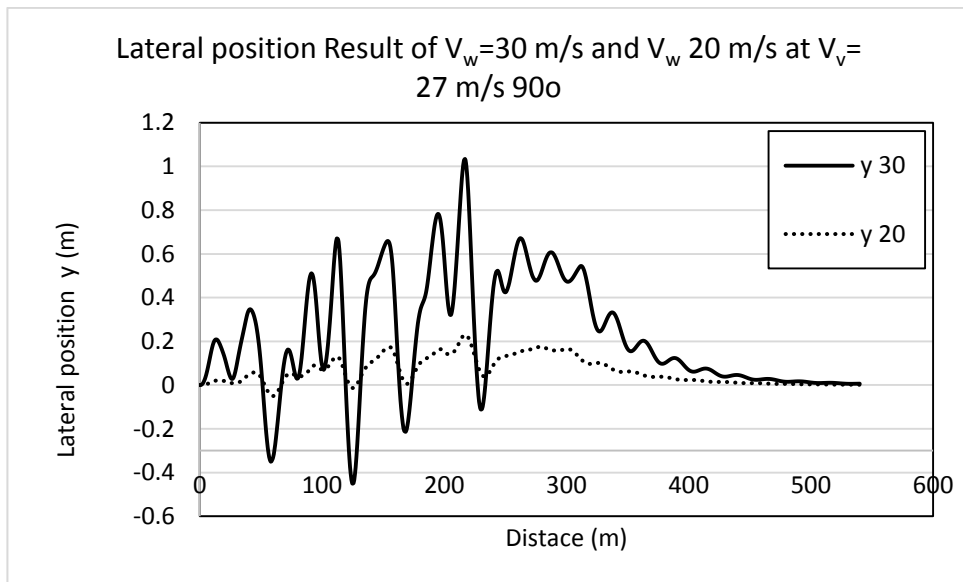


Figure (60)

Lateral displacement comparison between wind $V_w=30$ and 20 m/s at 90° , at $V_v = 27$ m/s.

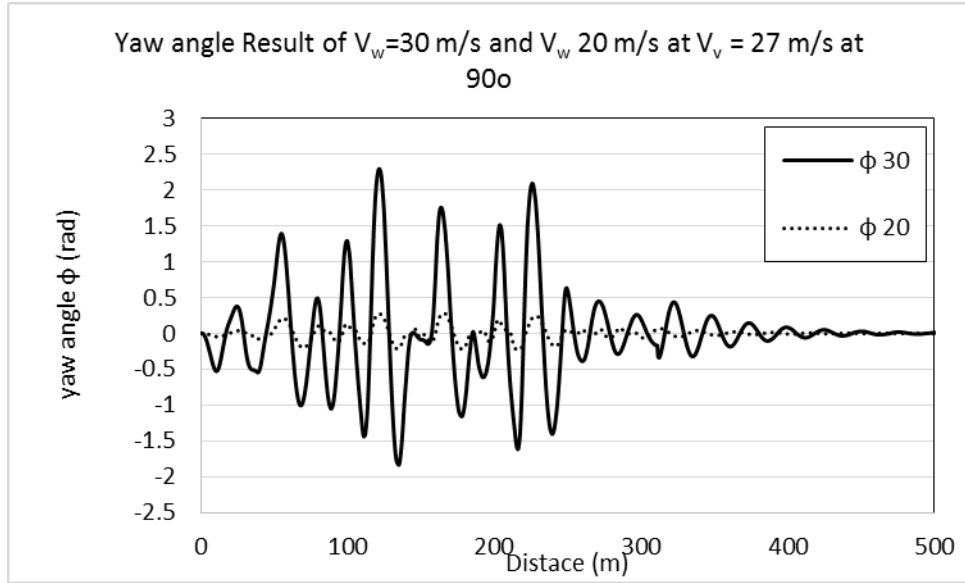


Figure (61)

Yaw angle comparison between wind $V_w=30$ and 20 m/s at 90° , at $V_v = 27$ m/s.

4.3.8. Effect of Vehicle velocity (V_v) discussion

A comparison between Lateral displacement between $V_v=80, 100$ and 120 km/h at $V_w=30$ m/s at 90° , is shown in Figure (62). It shows that displacement patterns are the same for all. Value increased a little between $V_v=80$ to 100 km/h with smoother control in $V_v=80$ km/h. Value increased 30% by increasing V_v to $=120$ km/h, loss of control noticed.

A comparison between yaw angle results between $V_v=80, 100$ and 120 km/h at $V_w=30$ m/s at 90° , is shown in Figure (63). It shows displacement patterns are almost the same for all. Value increased a little between $V_v=80$ to 100 km/h with smoother control in $V_v=80$ km/h. Value increased 100% by increasing V_v to $=120$ km/h, and loss of control noticed.

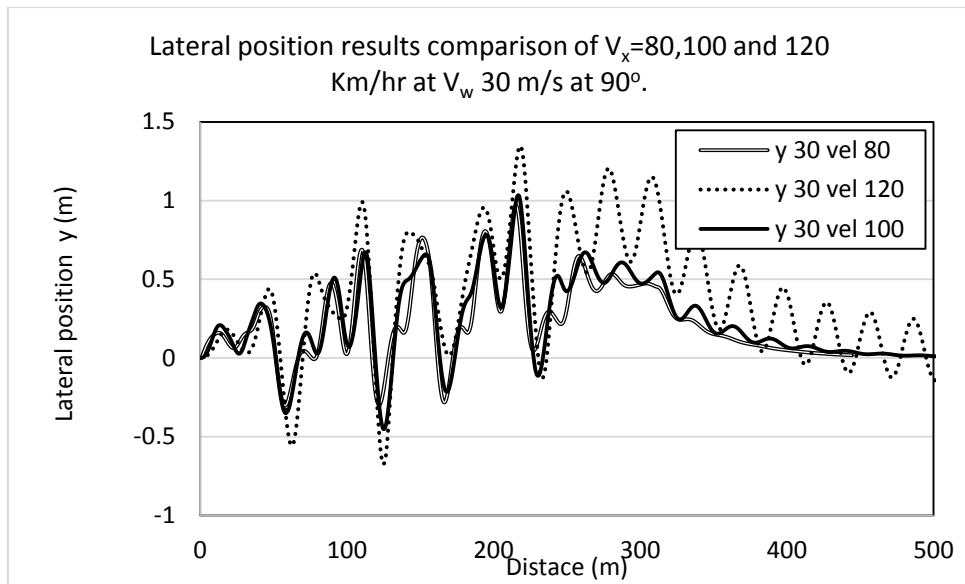


Figure (62)

Lateral displacement comparison between $V_x=80,100$ and 120 Km/hr. at V_w 30 m/s at 90° .

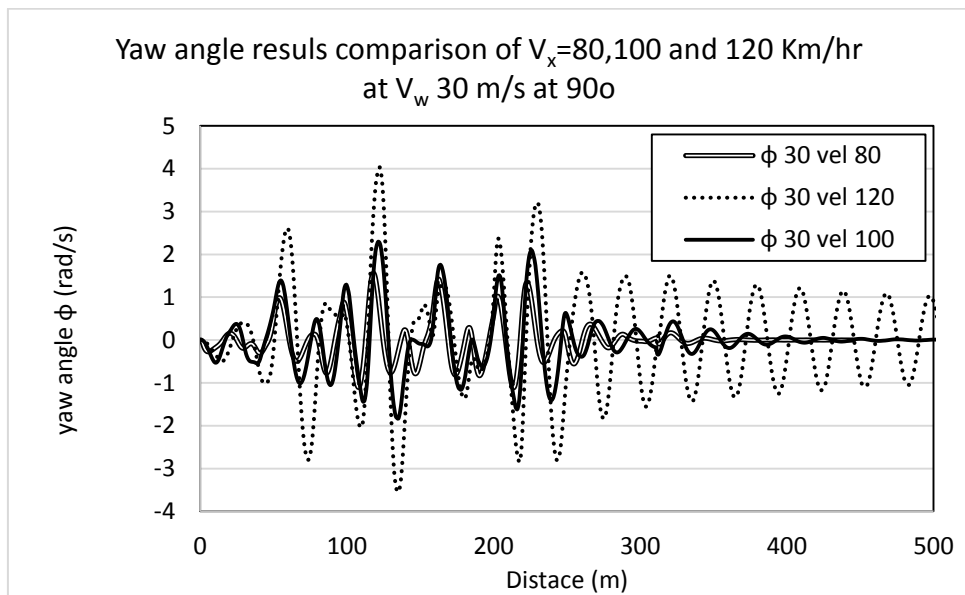


Figure (63)

Yaw angle results comparison of $V_x=80,100$ and 120 Km/hr. at V_w 30 m/s at 90° .

Chapter 5

Conclusions and Future Work

Chapter 5

Conclusions and future work

5.1 Conclusions

5.1.1. Aerodynamic simulation conclusion

The computational fluid dynamics (CFD) sliding mesh technique has been successfully developed and applied to the study of aerodynamic forces on vehicles overtaking a bridge in a crosswind. A 2-d simplified representation of a vehicle and a bridge focus on the effect of wind and vehicle velocities. Validation of the model with geometry are successfully matched with previous studies, Corin et al. (2008).

The investigation highlighted the effect of wind velocity and vehicle velocity on the aerodynamic forces acted on the vehicle.

ANSYS CFD simulation shows crosswind velocity on the bridge three times more than the free stream velocity with large variations in magnitude and direction. Wind direction may change wind contour after the bridge sails and maximum value is found when the wind velocity is perpendicular to the bridge. Findings regarding forces have the same pattern. Wind results match previous studies in patterns and magnitude, Charuvisita, Kimura and Fujino (2004a), and Rocchi et al. (2012)..

Moment is effected more than side force by vehicle velocity (V_v) changes. Increasing V_v to 120km/h gave double the value in 97 km/hr. Results match previous studies in patterns and magnitude, Charuvisita, Kimura and Fujino (2004b) and Argentini et al. (2011). Repeated patterns in wind and forces generated compared to previous studies found that they handle a single tower wake, whereas in this work six wakes with special arrangement have been shown.

A 3-d simulation will reveal a better understanding and more accurate result; however, comparing the results to this work will give the preferring bench an option to choose one of the two.

5.1.2. Vehicle dynamic simulation conclusion

Simulation of driver-vehicle systems subjected to wind forces are presented. The vehicle lateral dynamic model derived and a lead/lag compensator is used to represent the driver behavior. Simulation results of the vehicle stability domain are presented, the effects of driver parameters, vehicle forward velocity and side wind velocity are investigated.

Wind velocity changes deviate the vehicle more significantly than vehicle velocity changes, whereas vehicle velocity is critical to instability. Vehicle becomes unstable at forward velocity $V_x = 120$ km/h.

Wind forces deviate the vehicle from its original path in magnitude between half and 1 meter, which increases the chance of accidents. Stability is a serious concern in high crosswind conditions.

5.2 Future Work

- Experimental verification using measured data from the causeway will enrich the study.
- A 3D investigation of the bridge using sliding mesh technique can give a better understanding and more accurate wind profiles with more accurate aerodynamic loads. The shape of bridge sails will have a better representation and other parts of the bridge like side barriers and near ground wind effect on wind velocity should be taken into account.

- Motion over curved or arched causeways with crosswind should be investigated.
- Investigation from the driver-vehicle model can be extended to weight distributing and tire property effects.
- Simulation systems with more than 2-dof driver-vehicle simulation are expected to give more accurate results, but it should be fed with all axis forces and moments to obtain more advantage.

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Appendices

Appendix A

Tier properties to slip angle

Tier properties to slip angle

The axis system given by the Society of Automotive Engineers (SAE) is shown in Figure (A-1) (Society of Automotive Engineers 1965), where the origin of the axis system is the center of tire contact. A description of the system, the forces and moments is given in Table (A-1).

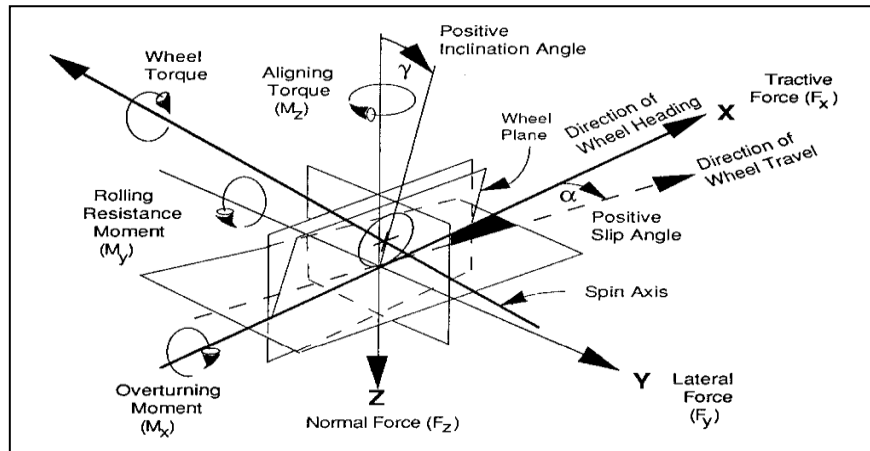


Figure (A-1)

The axis system by SAE.

Table (A-1): The axis system, forces and moments

	X-axis	Z-axis	Y-axis
Description	The intersection of the wheel plane and the ground plane with a positive direction forward.	Perpendicular to the ground plane with a positive direction downward.	It is in the ground plane, and its direction chosen to make the axis system orthogonal and right hand.
Forces	Tractive force F_x or longitudinal force	Normal force F_z	Lateral force F_y
Moments	Overturning moment M_x	aligning torque M_z	Rolling resistance moment M_y
Angle formation	Slip angle α between x-axis and direction of wheel travel.	Camber angle γ is the angle formed between the XZ plane and the wheel plane.	

Cornering properties of tires

Slip angle and cornering force

When a pneumatic tire is not subject to any side force, it will move along the wheel plane. If, however, a side force is applied to a tire, a lateral force (F_y) is developed at the contact patch and the tire will move along a path at an angle α . The wheel plane and the phenomenon of sideslip is mainly due to the lateral elasticity of the tire (Wong 2001). Figure (A-2) show how the lateral deformation of the tire develops slip angle.

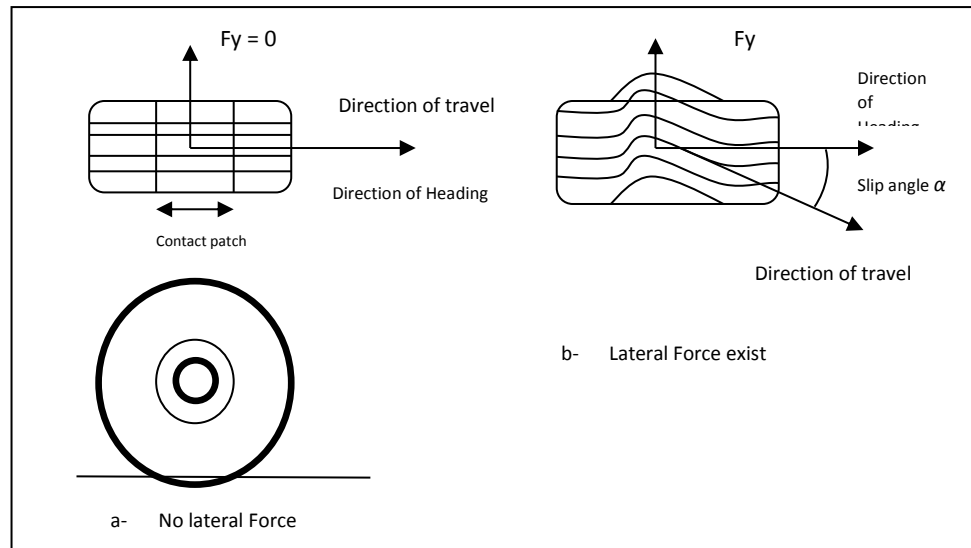


Figure (A-2)

Lateral deformation of the tire.

The lateral force developed at the tire-ground contact patch usually is called the cornering force $F_y\alpha$ when the camber angle of the wheel is zero.

To provide a measure for comparing the cornering behavior of different tires, a parameter called cornering stiffness $C\alpha$ is used. It is defined as the derivative of the cornering force $F_y\alpha$ with respect to slip angle α valuated at zero slip angle:

$$C_{\alpha} = \frac{dF_y}{d\alpha} \quad \text{at } \alpha = 0$$

Where cornering stiffness C_{α} (N/rad) represent the slope of the initial portion of the tire curve as in figure (A-3) (Society of Automotive Engineers 1965).

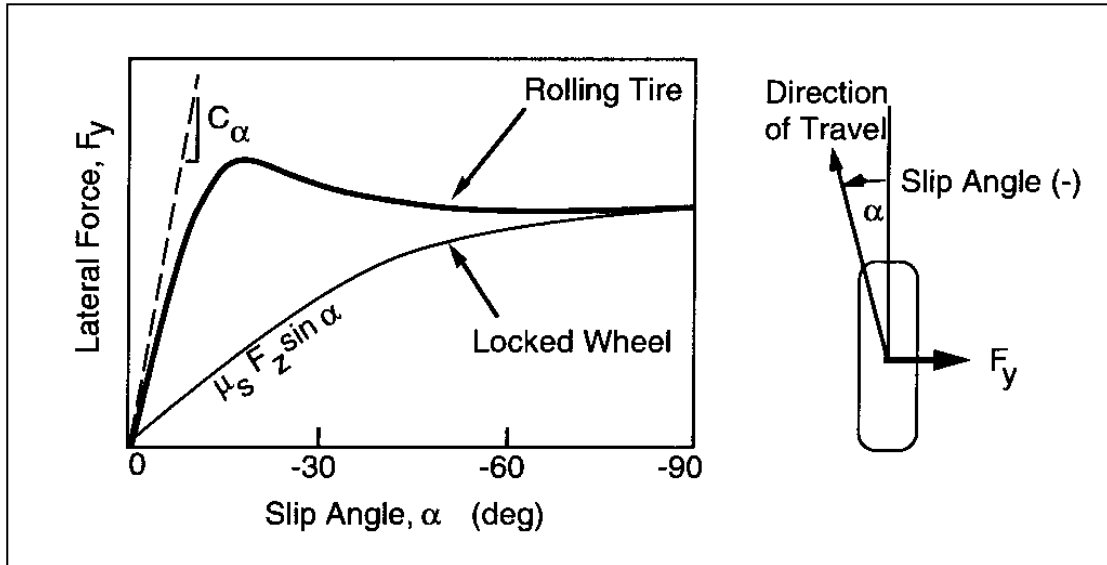


Figure A-3:
Tire lateral force properties (Society of Automotive Engineers 1965).

A number of factors affect the cornering behavior of pneumatic tires, such as size and construction of the tire in general; the normal load on the tire strongly influences the cornering characteristics. Inflation pressure usually has a moderate effect on the cornering properties of a tire. In general, the cornering stiffness of tires increases with an increase in the inflation pressure (Wong 2001) (Society of Automotive Engineers 1965).

Slip angle and aligning torque

The torque generated because the side force F_s , and the cornering force $F_y\alpha$ are usually not collinear. This gives rise to a torque commonly known as the aligning or self-aligning torque.

While driving, driving torque increases the aligning torque for a given slip angle while a braking torque has the opposite effect. Inflation pressure and normal load effect the size of the tire contact patch, which also effects the aligning torque. Higher than normal load and lower inflation pressure can result in an increase in the aligning torque.

Appendix B

Steps of repeating Corin, He, and Dominy (2008) CFD
experiment.

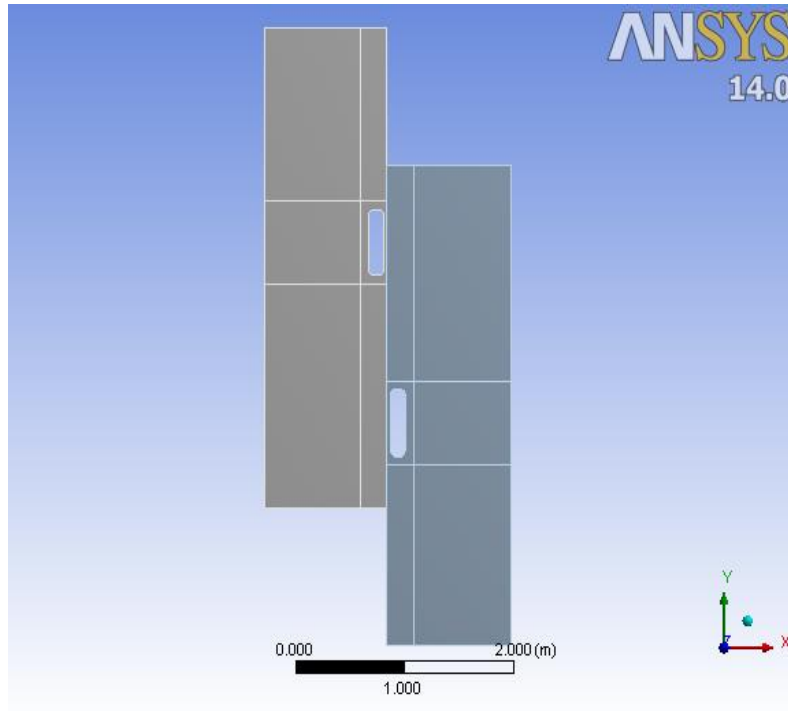


Figure B-1:
Vehicle zones in 2-d generated by Solidworks® transferred to Design Modeler.

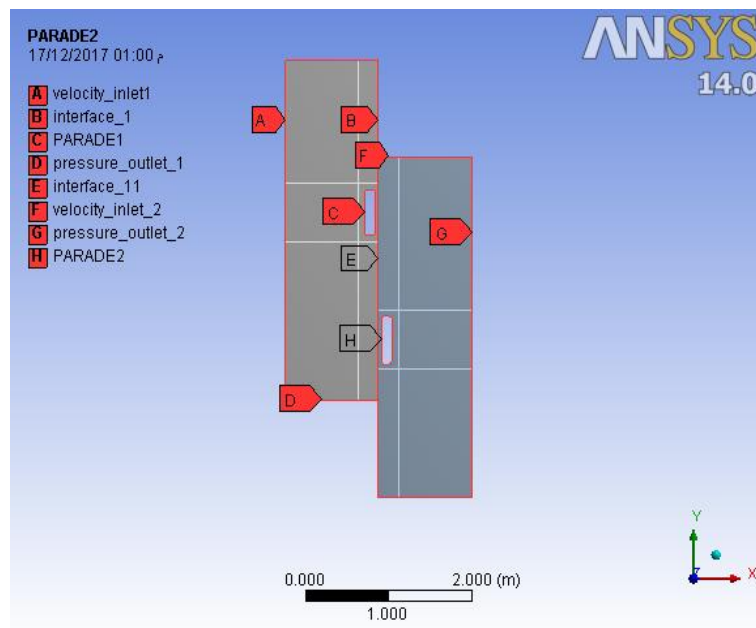


Figure B-2:
Zones boundary naming in Design Modeler.

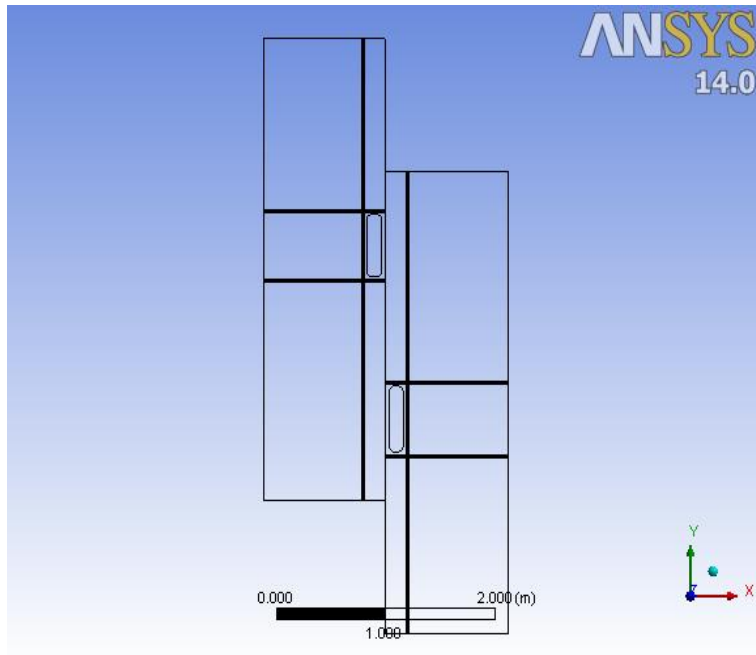


Figure B-3:
Zones dividing introduction to meshing.

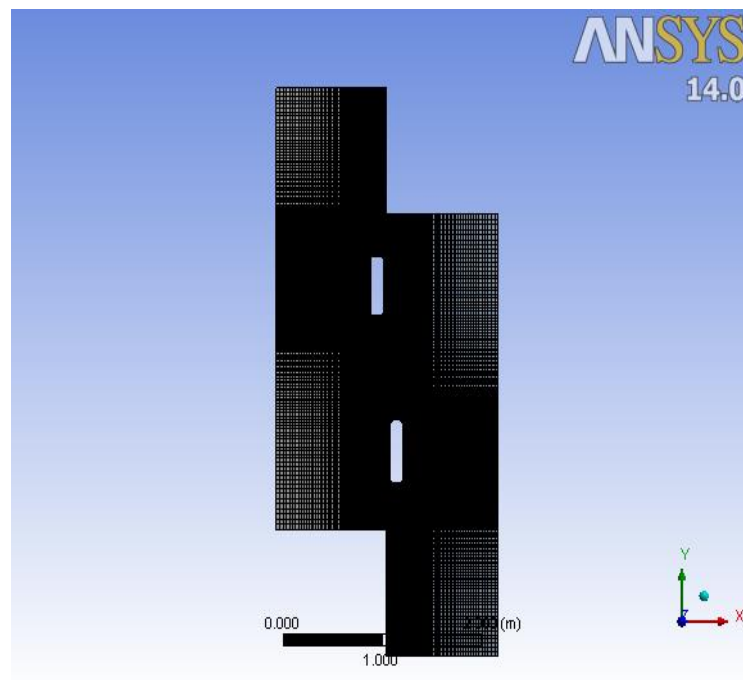


Figure B-4:
Divided zones meshing.

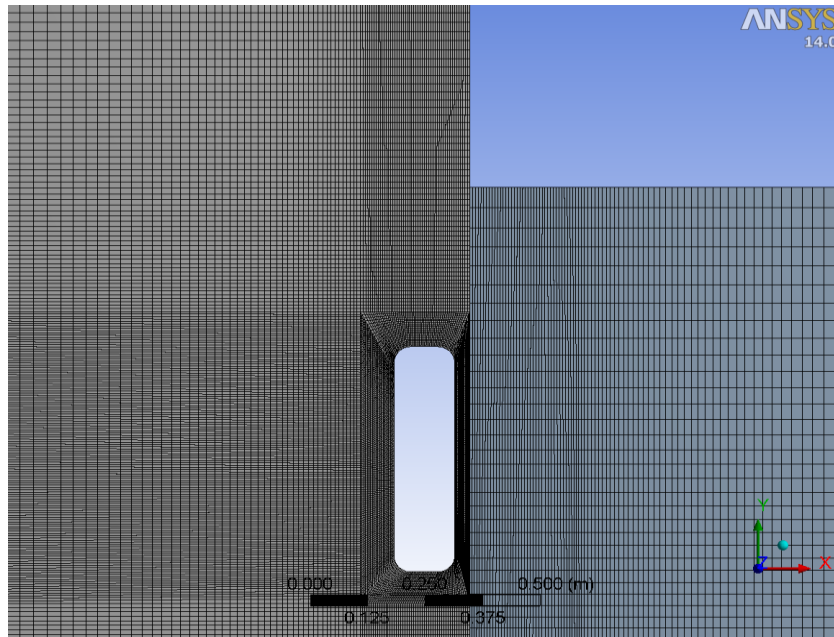


Figure B-5:
Zoomed in divided zones meshing.

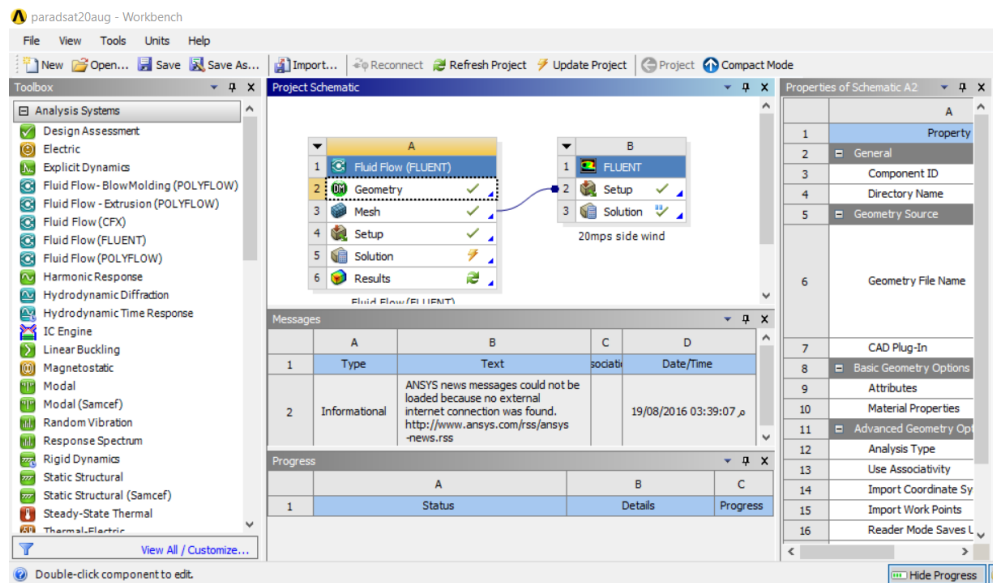


Figure B-6:
Ansys Fluent problem setup.

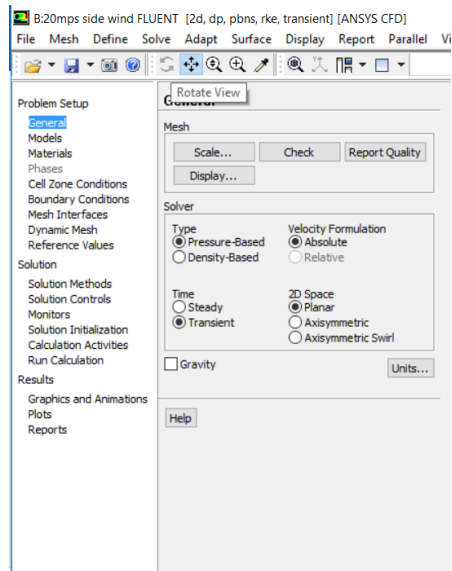


Figure B-7:

Ansys Fluent general setup.

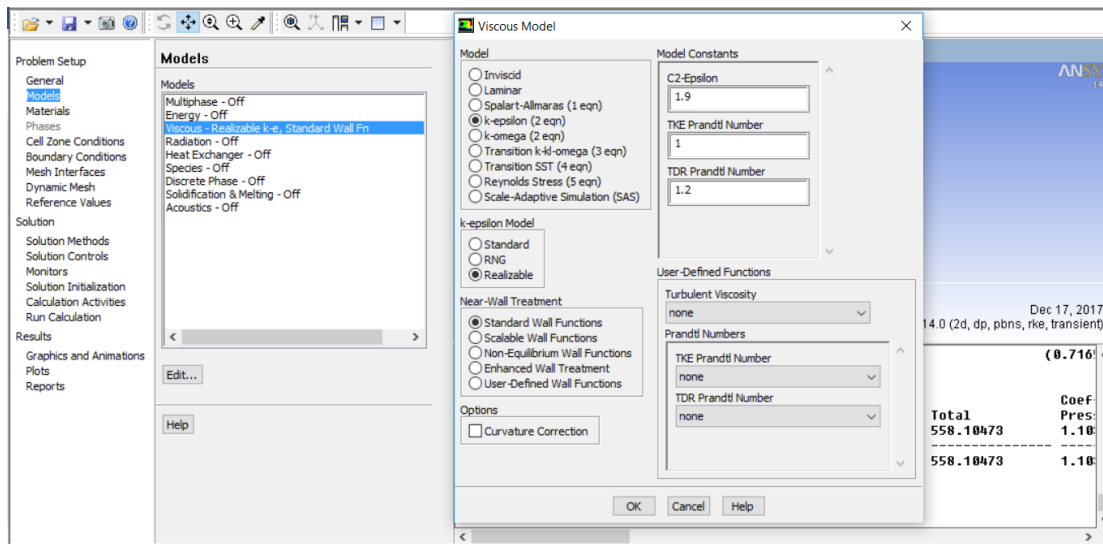


Figure B-8:

Ansys Fluent model setup.

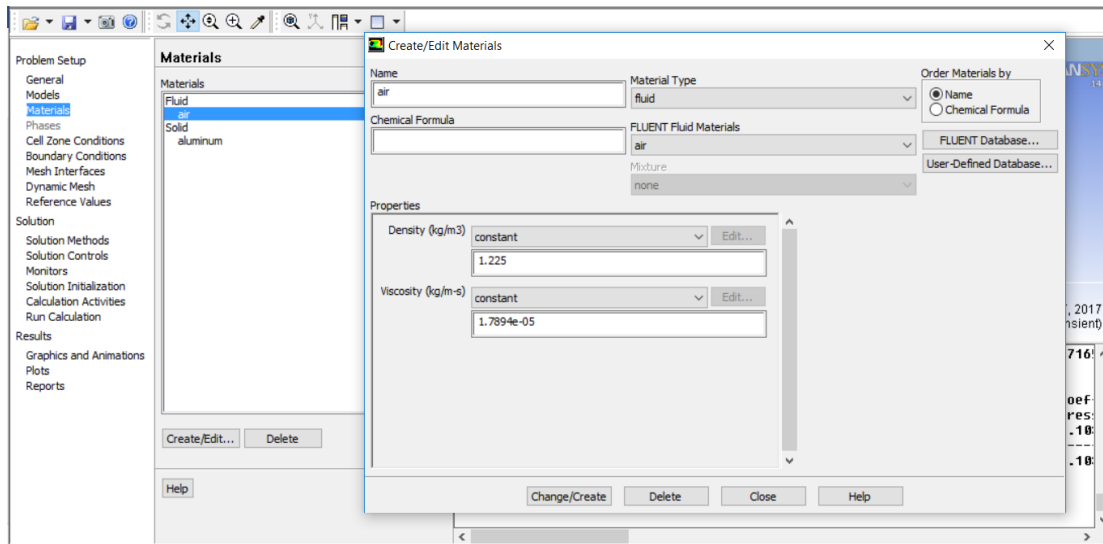


Figure B-9:

Ansys Fluent material setup.

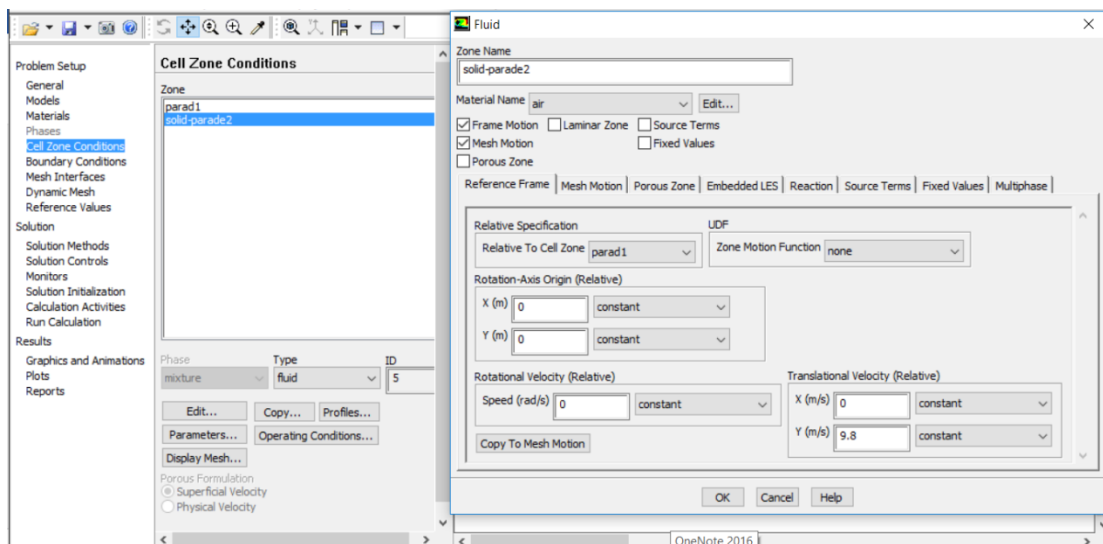


Figure B-10:

Ansys Fluent cell zone setup.

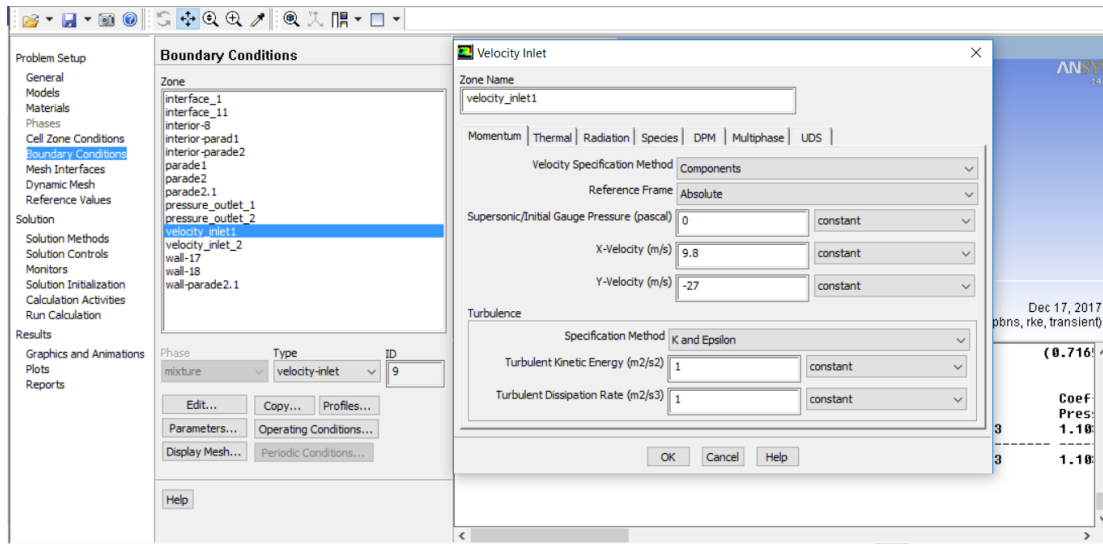


Figure B-11:

Ansys Fluent boundary condition setup.

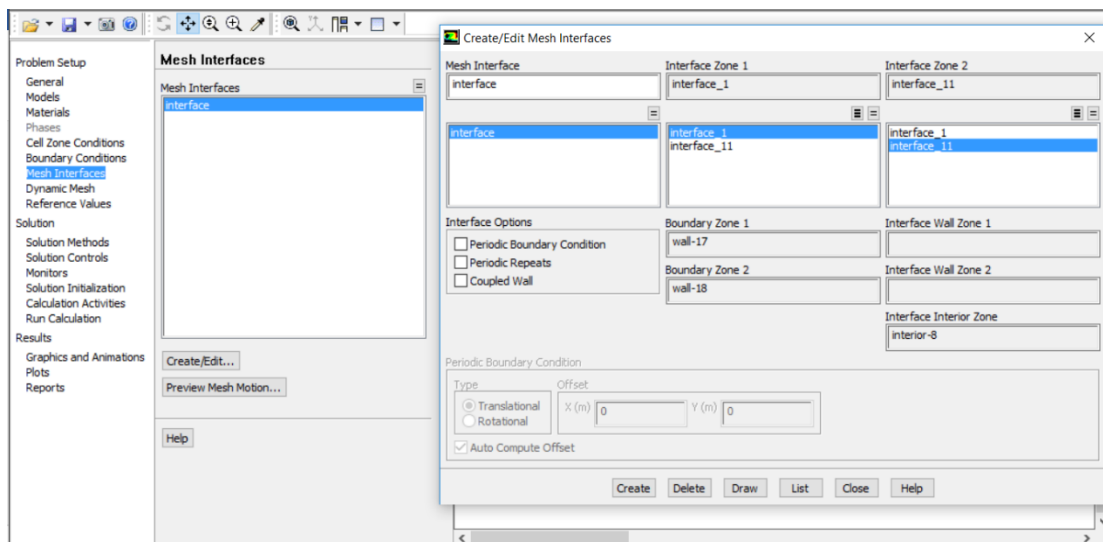


Figure B-12:

Ansys Fluent mesh interface setup.

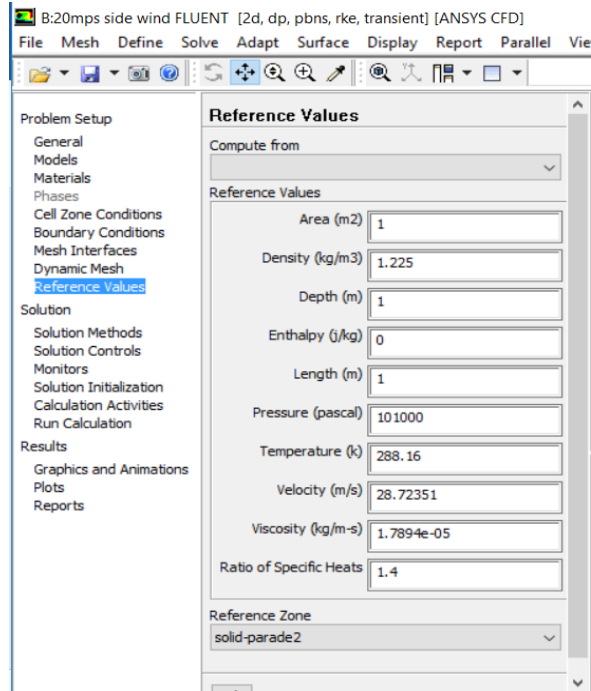


Figure B-13:

Anslys Fluent reference value setup.

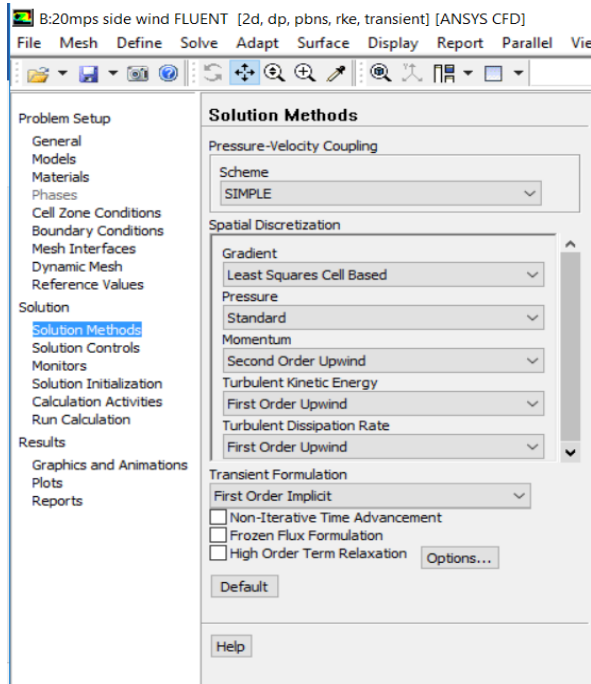


Figure B-14:

Anslys Fluent solution method setup.

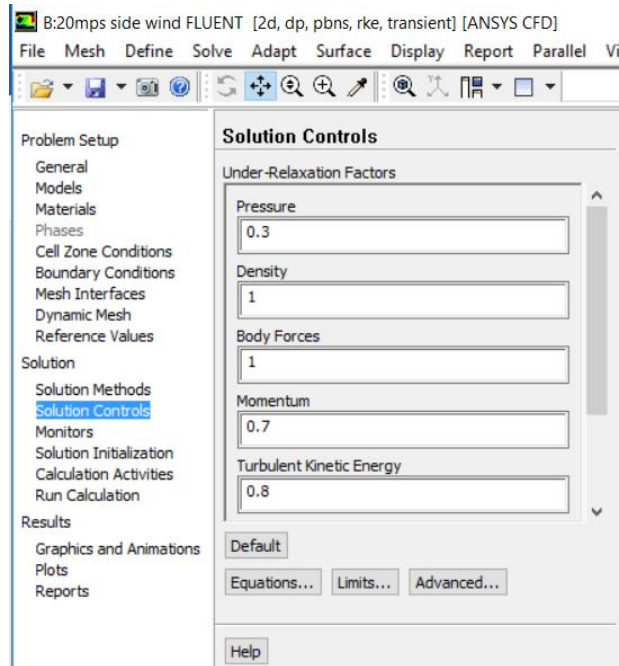


Figure B-15:

Ansyes Fluent solution control setup.

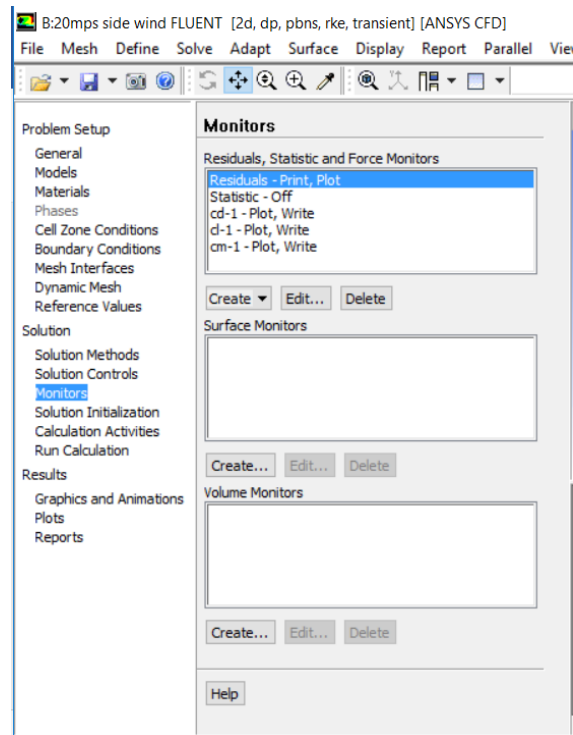


Figure B-16:

Ansyes Fluent solution monitor setup.

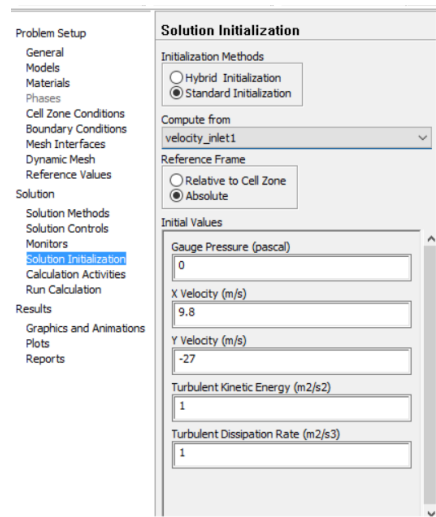


Figure B-17:

Ansys Fluent solution initialization setup.

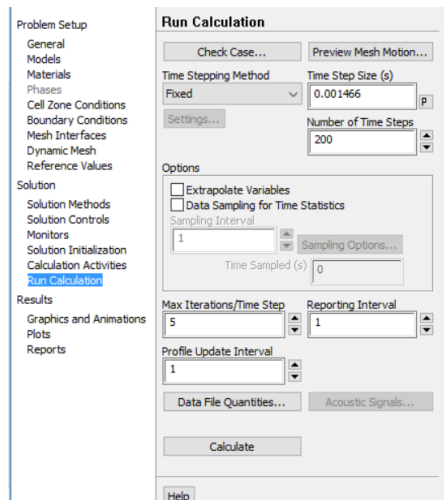


Figure B-18:

Ansys Fluent solution run calculation setup.

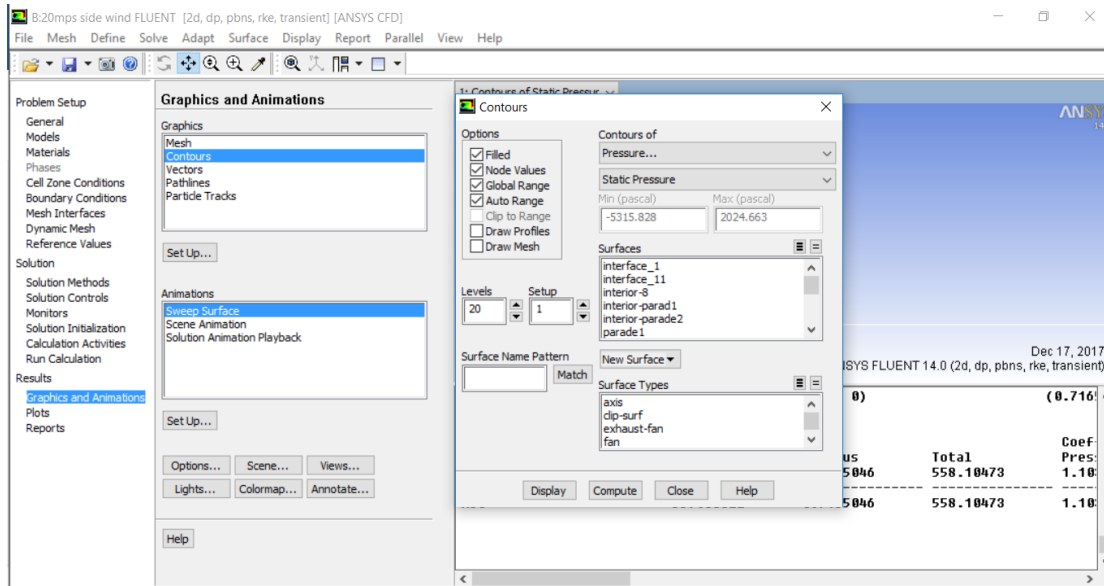


Figure B-19:

Ansyes Fluent Results graphics and animation setup.

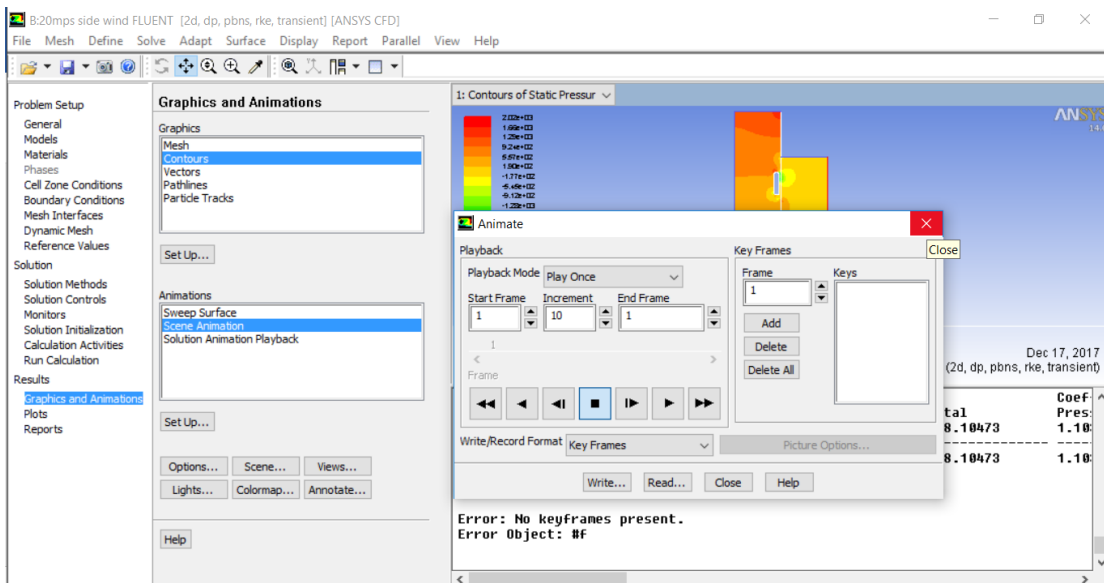


Figure B-20:

Following Ansyes Fluent Results graphics and animation setup.

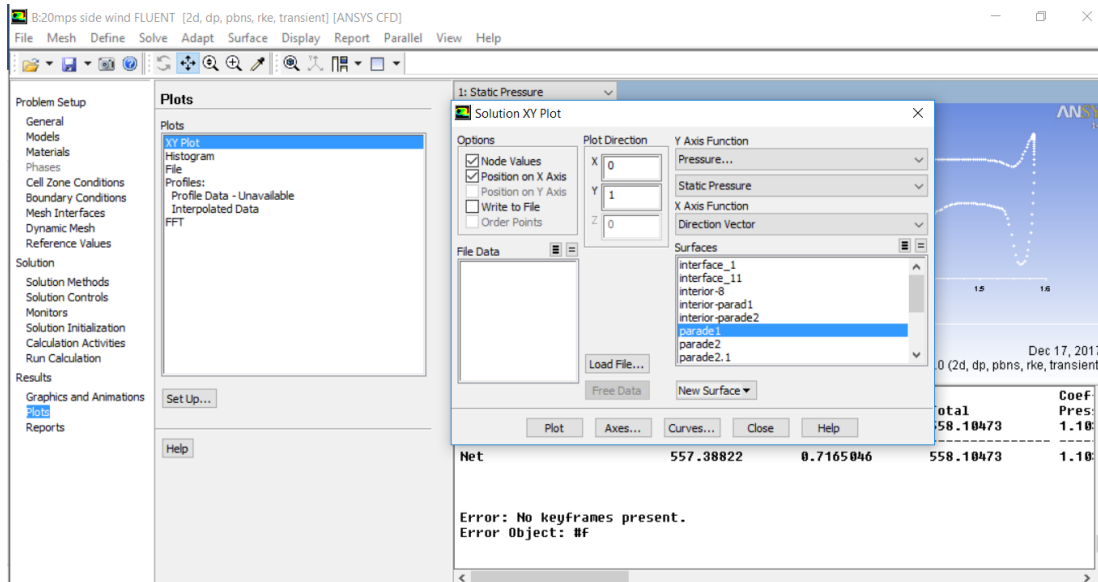


Figure B-21:

Ansyes Fluent Results plots setup.

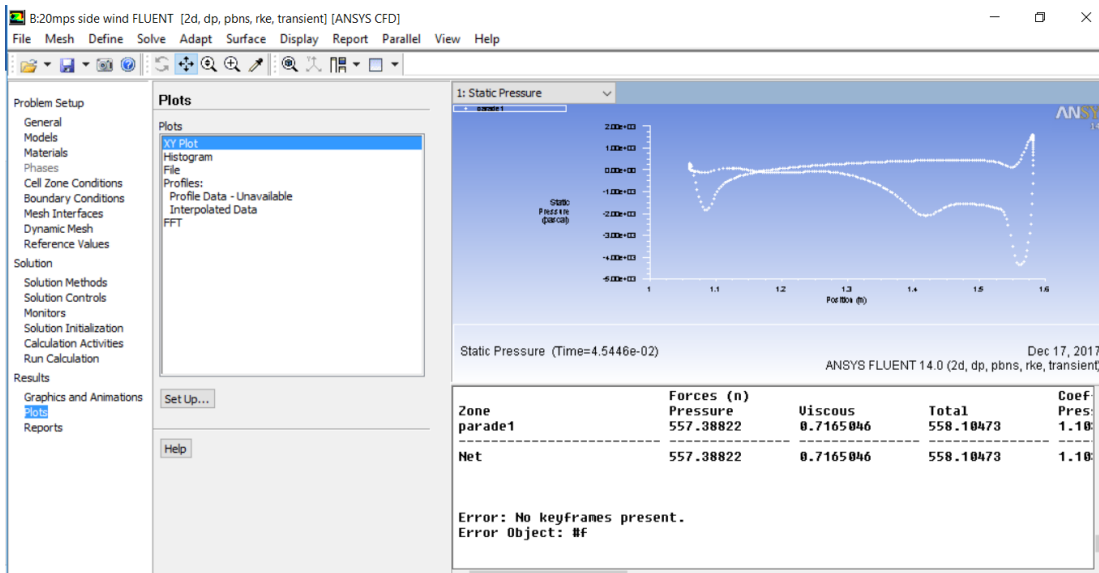


Figure B-22:

Following Ansyes Fluent Results plots setup.

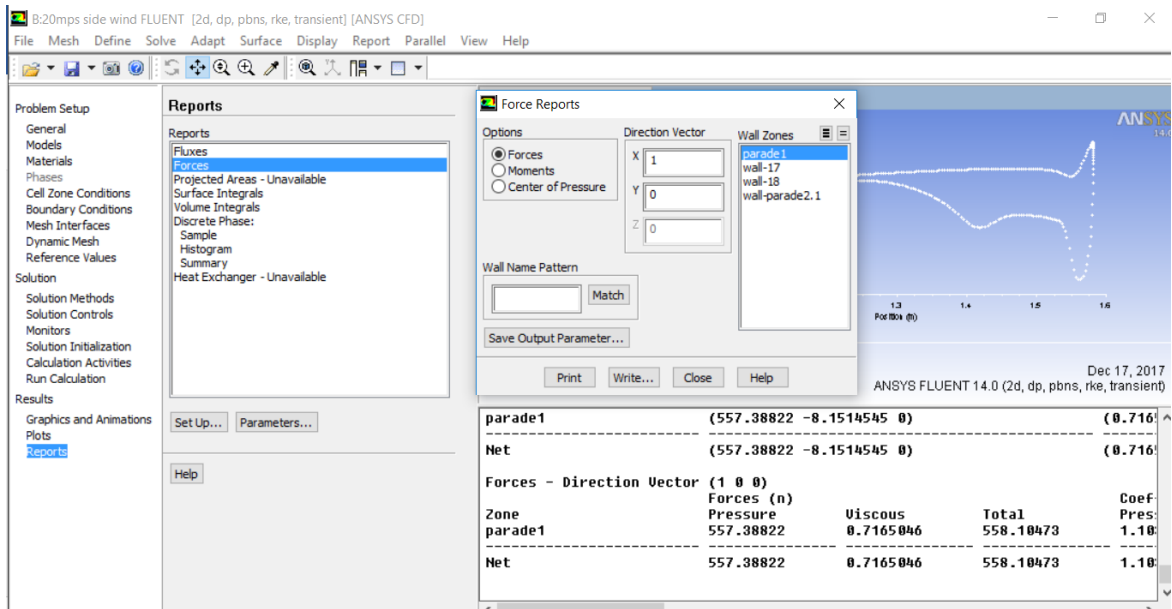


Figure B-23:

Ansyes Fluent Results Forces Report setup.

Appendix C

**ANSYS® Software technical setting for aerodynamic
simulation.**

ANSYS® Software technical setting.

As engineering simulation technology suite, mainly used to help in design and optimizing products, computational fluid dynamics is one of its capabilities like ANSYS FLUENT CFD. ANSYS® 14.0. Version is used in this research.

ANSYS FLUENT is a CFD software workbench with a modeling capability to model flow, turbulence and heat transfer, such as airflow around vehicle or combustion in a piston. It contains several software designs related to each other,

- ANSYS Design Modeler, used to create or import geometry
- ANSYS Meshing application, used to generate computational mesh through the flow volume.
- ANSYS FLUENT, used to setup the parameters, control the simulation, display and report results.
- ANSYS CFD-Post, used to display and report results.

ANSYS Fluent Design Modeler

The three zones generated are imported to Design Modeler with each zone in separated process to prevent merging. A full setup of the three zones is in Figure (C-1). The zones and outer boundary are named which helps the program to suggest suitable boundary conditions.

ANSYS Meshing Application

The computational mesh design was Multi-block structured meshes with eight mesh blocks for bridge zone, six blocks for vehicle zone and two blocks for after vehicle zone shown in Figure (C-2). The multi block was used to control the meshing process easily. Enlargement ratios were used between

1.2 and 1.3 to give appropriate mesh expansion, number of nodes on the vehicle surface is 250, and number of mesh cells in the computational domain was 198607 mesh cells.

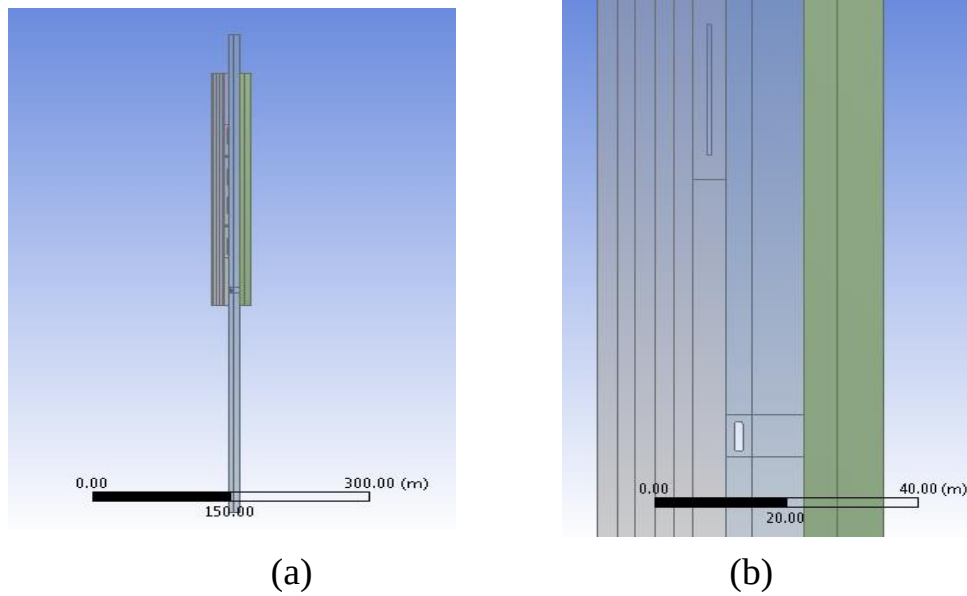


Figure (C-1)

The zones by Design Modeler, a) Full setup, b) Zoomed view.

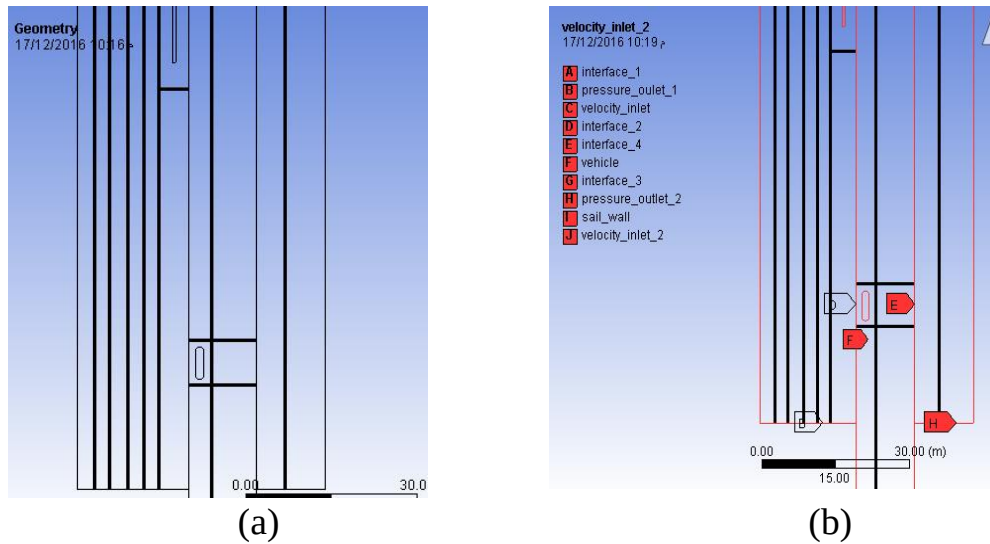


Figure (C-2)

Sketch shows a) Multi-block structured and b) Naming zones and boundaries.

Domain and boundary conditions

The outer boundaries of the computational domain were either flow inlet or pressure outlet depending on the flow direction where flow velocity and direction were set. At the boundaries between zones interface boundary where set to interchange the information while mesh slide.

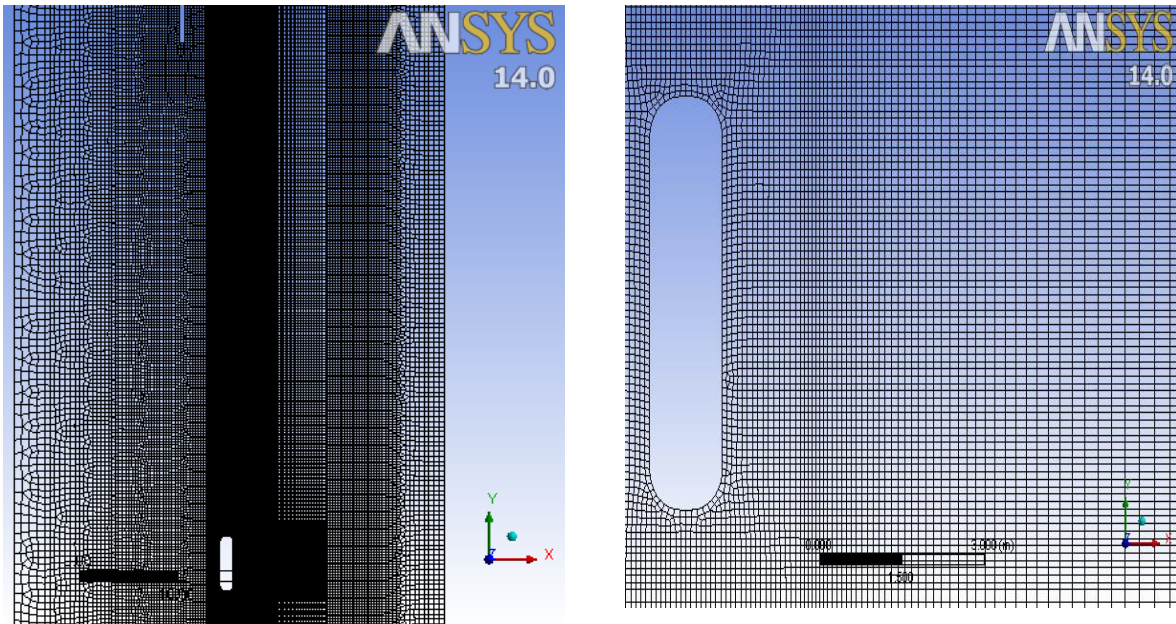


Figure (C-3)

Part of a) domain mesh, and b) Vehicle zoomed mesh.

ANSYS Fluent setup

Problem setting/ General Setting

General setting in problem setup was used to check the mesh quality and the solver options. For a dynamic simulation, the pressure-based transient with planner solver were set, see Figure (C-4a).

Models setting

A viscous model with standard K- ϵ and standard wall functions used, Figure (C-4b).

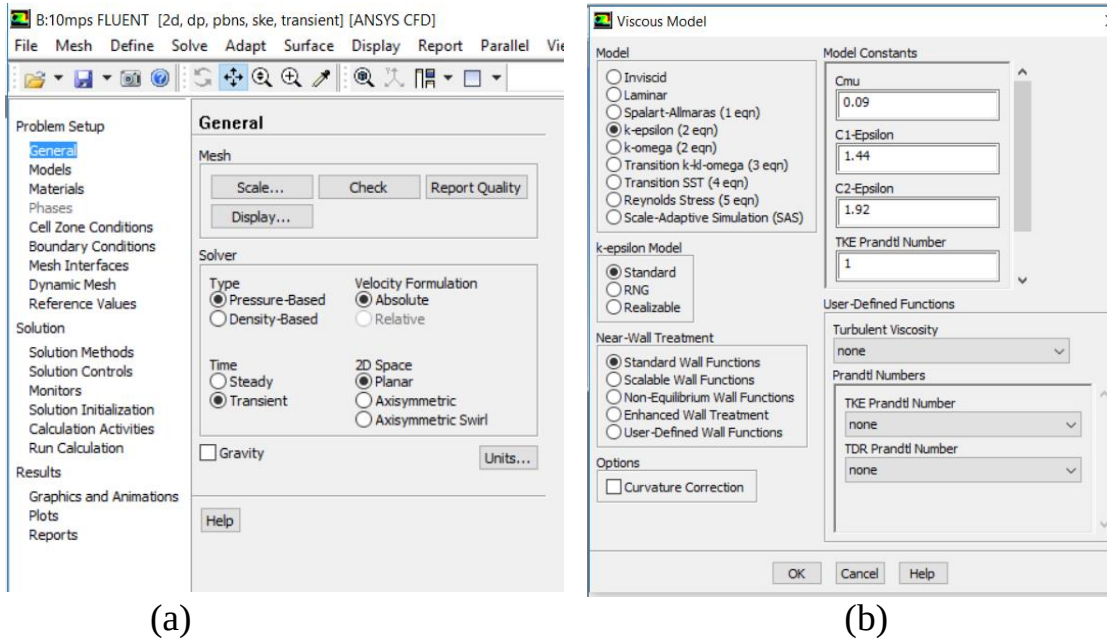


Figure (C-4)

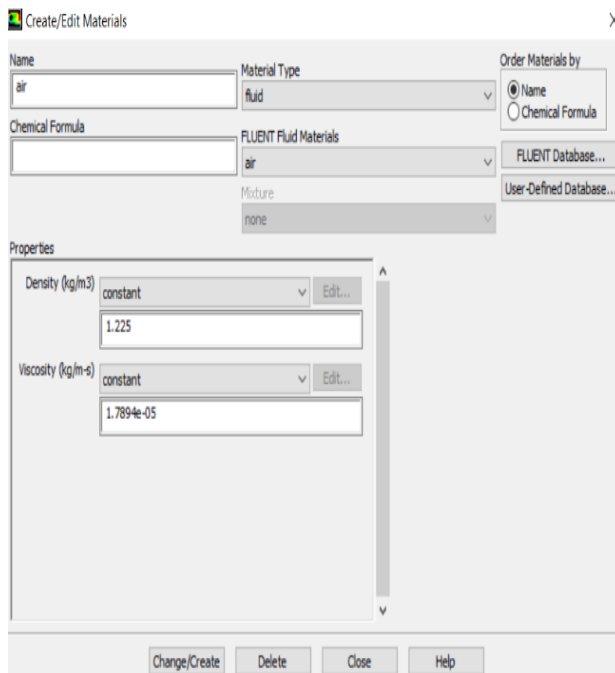
Ansys Fluent problem setup, a) General setting, b) Models setting.

Material setting

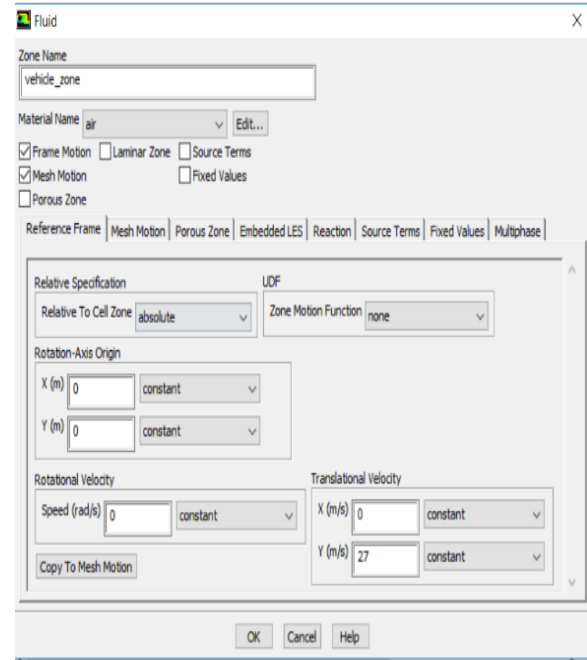
The flow volume set as air with density (ρ) = 1.225 (kg/m³) and Dynamic viscosity (μ) = 1.7894 e⁻⁵ (kg/m-s), figure (C-5a).

Cell zone condition setting

Bridge zone and after zone were set with no frame motion nor mesh motion. Vehicle zone translational sliding mesh and frames with different velocities (22.22 m/s, 27 m/s and 33.33), toward a positive y-axis. Figure (C-5b) shows vehicle Cell zone condition setting.



(a)



(b)

Figure (C-5)

Ansys Fluent problem setup, a) Materials setting, b) Vehicle Cell zone condition setting.

Boundary condition Setting

The boundary conditions of the geometry three zones is listed in Table (C-1); Velocity inlet (velocity of crosswind) had a different value and direction in the simulation.

Table (C-1)

The domain zones and geometry boundary conditions.

#	Geometry	Boundary condition	Zone
1	Bridge sails and columns	wall	Bridge zone
2	Top and left boundary	Velocity inlet (velocity of crosswind)	
3	Bottom boundary	Pressure outlet	
4	Right boundary	Interface with vehicle zone	
5	Vehicle	Wall	Vehicle zone
6	Left boundary	Interface with bridge zone	
7	Right boundary	Interface with after vehicle zone	
	Top boundary	Velocity inlet (velocity of crosswind)	
8	Bottom boundary	Pressure outlet	After vehicle zone
9	Left boundary	Interface with after vehicle zone	
10	Right and bottom boundary	Pressure outlet	
11	Top boundary	Velocity inlet (velocity of crosswind)	
12	Other	Interior	

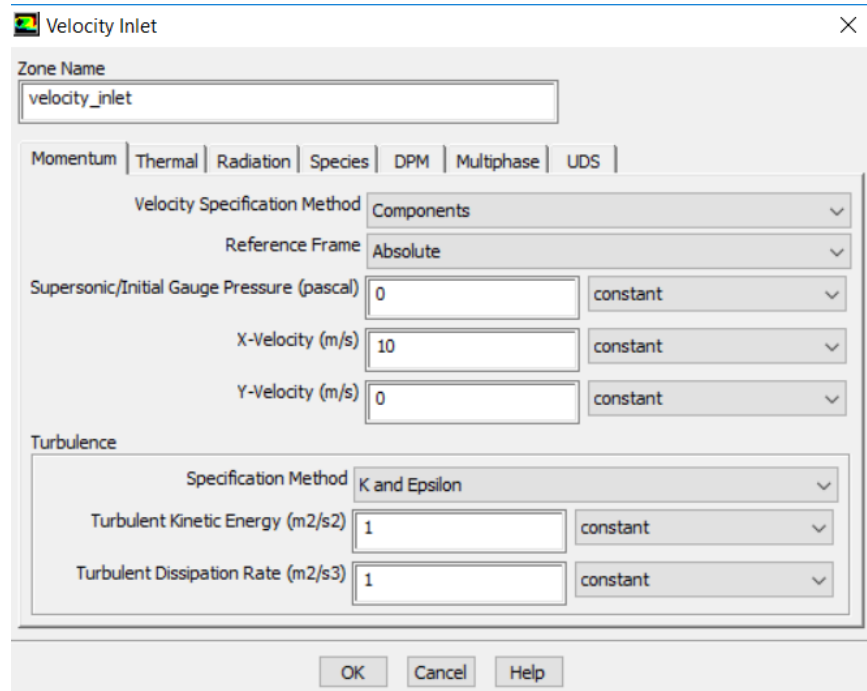


Figure (C-6)

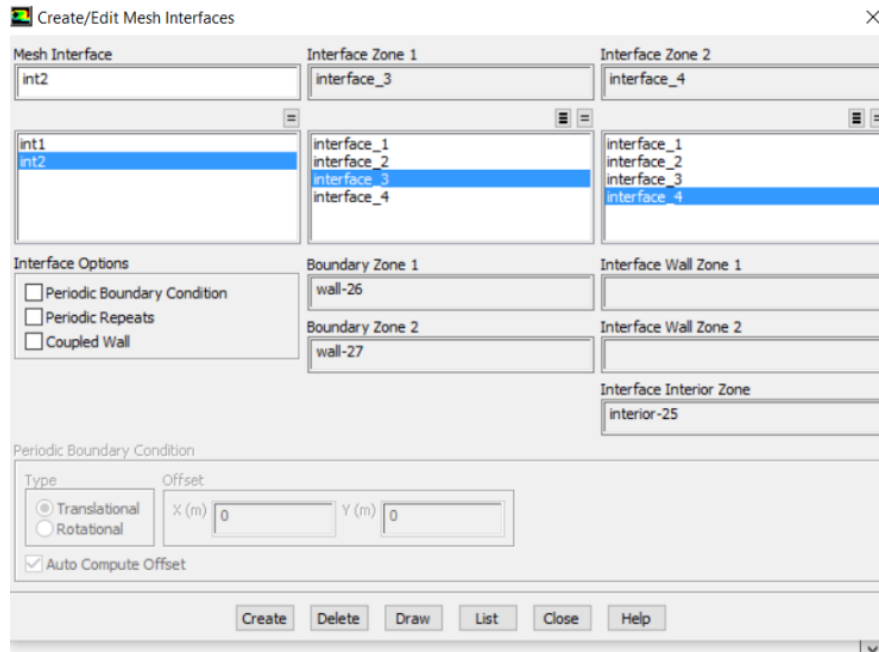
Ansyes Fluent problem setup,
Velocity inlet boundary condition setting.

Mesh Interface Setting

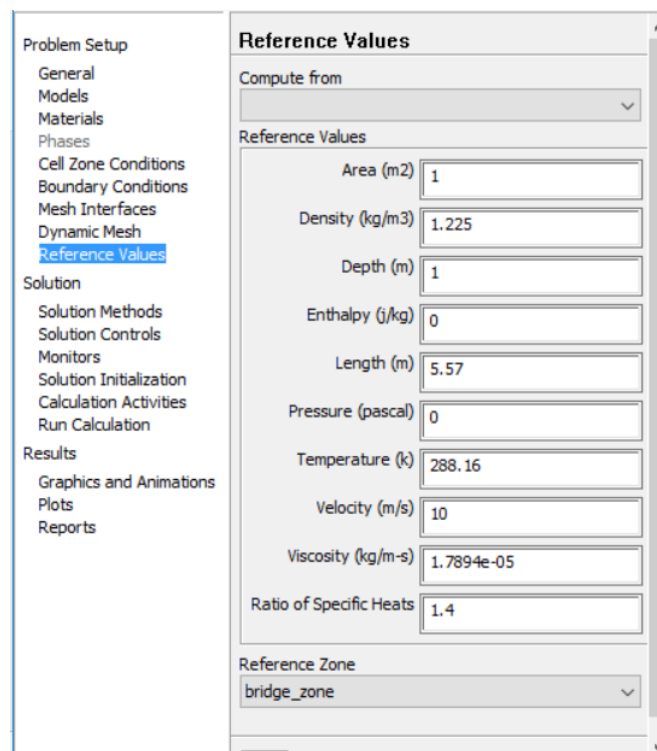
As mentioned in Table (C-1), the boundaries between the three zones were set as interface. Figure (C-7a) shows one of the settings.

Reference value setting

The following values were used as reference values, air density (ρ) = 1.225 (kg/m^3), dynamic viscosity (μ) = 1.7894e^{-5} (kg/m-s), Area =1 (m^2), depth=1 (m), vehicle length =5.57 (m), pressure = 101 (kpa), and temperature=288.16 (k), see Figure (C-7b). The area setting as a unity was utilized because of the dependence of area in drag and side force calculations by the software. The values were adjusted later.



(a)



(b)

Figure (C-7)

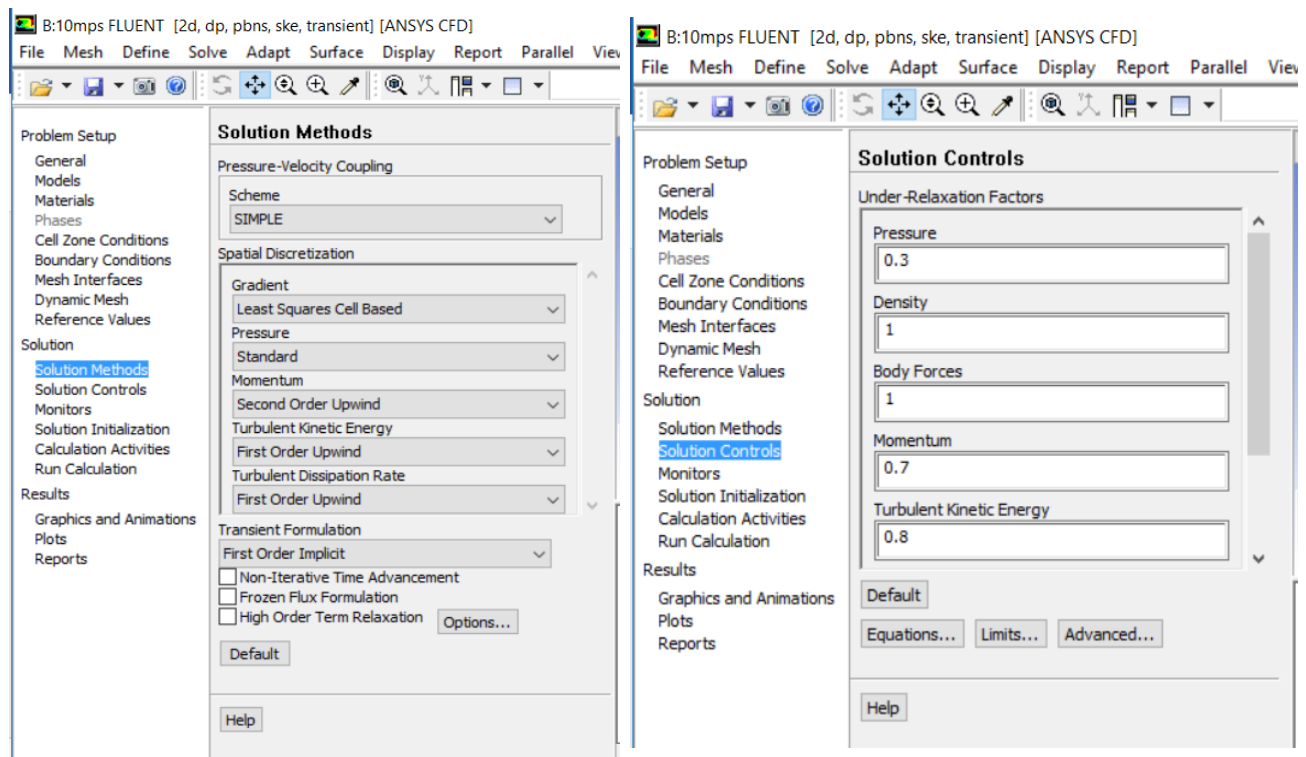
Ansys Fluent problem setup, a) Mesh interface Setting and b).Reference values Setting.

Solution setting

Solution setting used to set solution methods, solution control, monitors, solution initialization, calculation activity and calculations runs.

Solution methods & Solution controls

Solution methods default set used, for details see figure (C-8a),
Solution controls default set used. For details see figure (C-8b).



a)

b)

Figure (C-8)

Ansyes Fluent problem setup, a) Solution Methods setting, b) Solution controls.

Monitors Solution Initialization

Residual monitors are used to check the convergent. Coefficient of drag (C_d), Coefficient of lift (C_l) (which will be replaced by Coefficient of side force (C_s)) and Coefficient of moment (C_m) monitors were set to measure the vehicle's aerodynamic forces. The three coefficients were observed during calculation activity and saved in a separate file for every run. See Figure (C-9 a).

Solution Initialization

Standard initialization computed from velocity inlet-1 (Bridge zone top and left boundary) see figure (C-9 b).

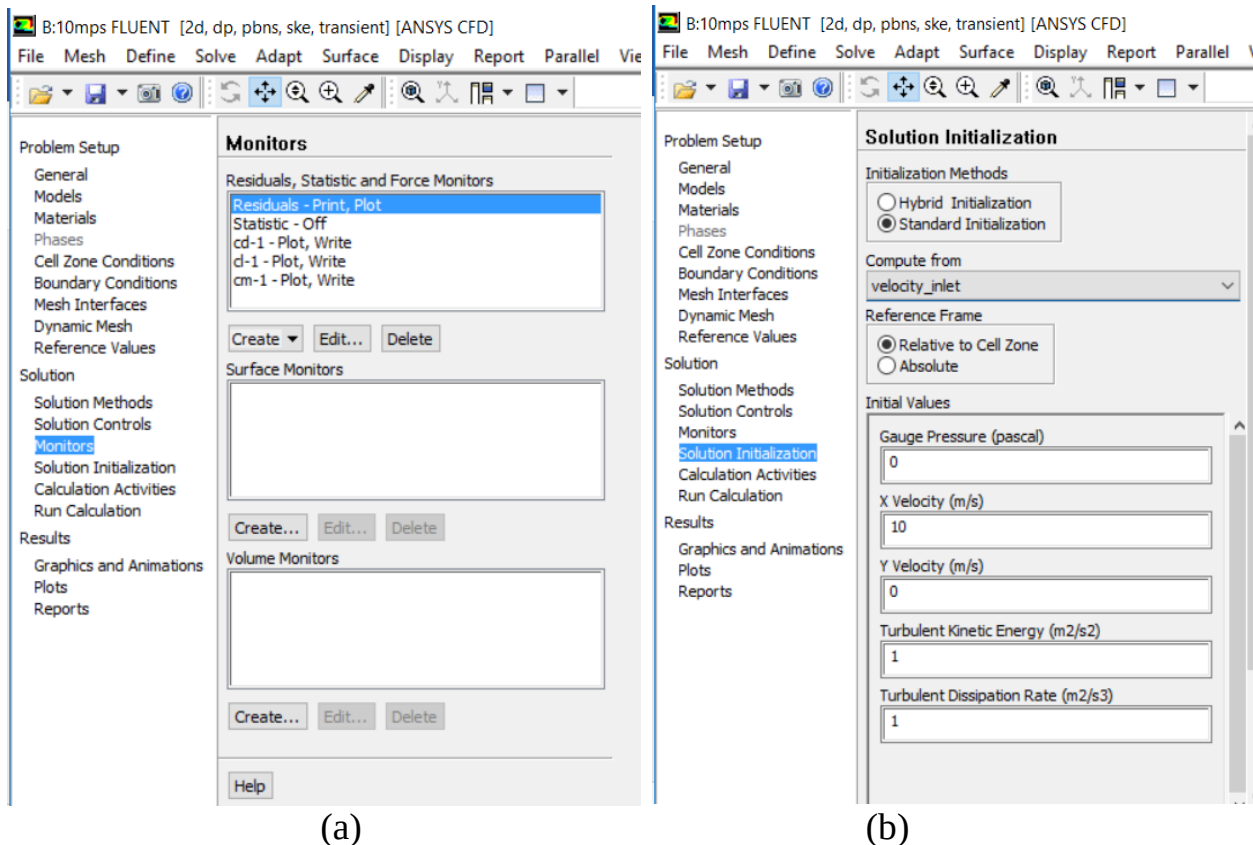


Figure (C-9)

Ansyes Fluent problem setup, a) Monitors and b) Solution Initialization.

Calculation Activities

Data save was consuming time and memory space. Many trials were done to save the force results as files or exported data. Due lack of experience and the time needed for trials stopped, and animation sequences are saved for demonstration purposes.

Run Calculation

For calculation of the time step dependency of the solution tested using double factors, a time step of 180, 360 and 720 is tested. 360 provides an adequate solution accuracy and accepted computation time. Time step size=0.032 (s) and to allow the results to converge a 20 iteration per time step were used total time is 11.52 (s), see Figure (C-10).

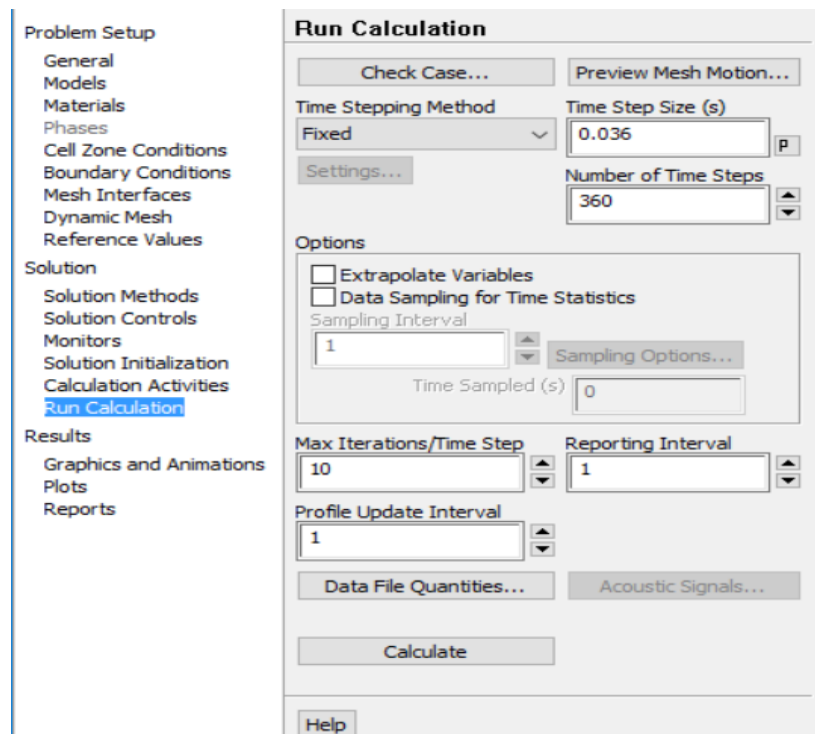
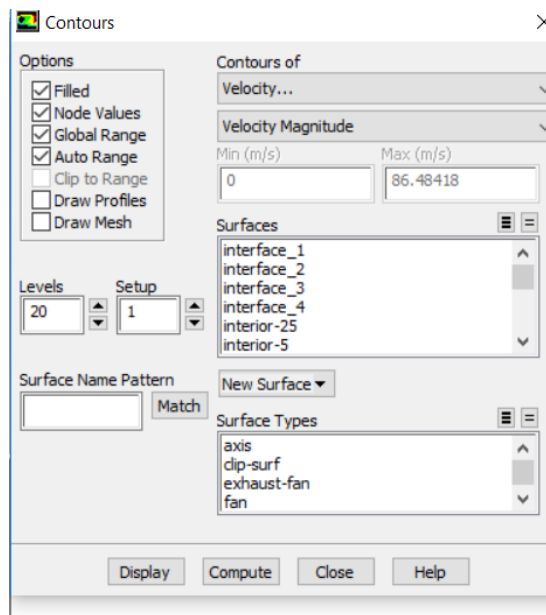


Figure (C-10)

Ansys Fluent problem setup, run calculation setting.

Results setting Graphics and animations

After the solver completes calculations, there are two ways to get the results; first from the solver result directly or from post-processing. The first format is used. Many types of graphics can be generated; pressure and velocity contours and vectors are used. Animation is saved and play pack for visualization and demonstration is shown, see Figure (C-11).



(a)



(b)

Figure (C-11)

Ansys Fluent Result Graphics and Animation setup,

a) Graphics Contours and b) Animation set.

Plots

X-Y plots used to find (C_p) on the vehicle wall.

Reports

Pressure and viscous forces, in X and Y directions are detailed in force report. The report contain only the last iteration result.

Appendix D

MATLAB and Simulink models

(Appendix D-1)

MATLAB and Simulink model simulate open loop vehicle behavior to given step

File name: lanechangem.m

```
clear all

%handling Characteristics open loop
%-----
W=19600; L=5.57; Lf=L/2; Lr=L/2;
Cf=30000; Cr=Cf;
g=9.81; Iz=500;
Nsr=20;
Vx=216/3.6;
m=W/g;

A11=-(2*Cf+2*Cr)/(Vx*m);
A12=-Vx-(2*Lf*Cf-2*Lr*Cr)/(m*Vx);
A21=-(2*Lf*Cf-2*Lr*Cr)/(Iz*Vx);
A22=-(2*Lf^2*Cf+2*Lr^2*Cr)/(Vx*Iz);

B1=2*Cf/m; B2=2*Lf*Cf/Iz;

A=[ A11 A12; A21 A22];
B=[ B1 ; B2 ];

eig(A)
Plot
subplot(3,1,1),plot(t_y_w(:,1),t_y_w(:,4));
ylabel('delta(rad)');grid;
subplot(3,1,2),plot(t_y_w(:,1),t_y_w(:,2));
ylabel('Vy (m/s)');grid;
subplot(3,1,3),plot(t_y_w(:,1),t_y_w(:,3));
ylabel('omega (rad/s)');grid;
xlabel('Time (s)');grid;
```

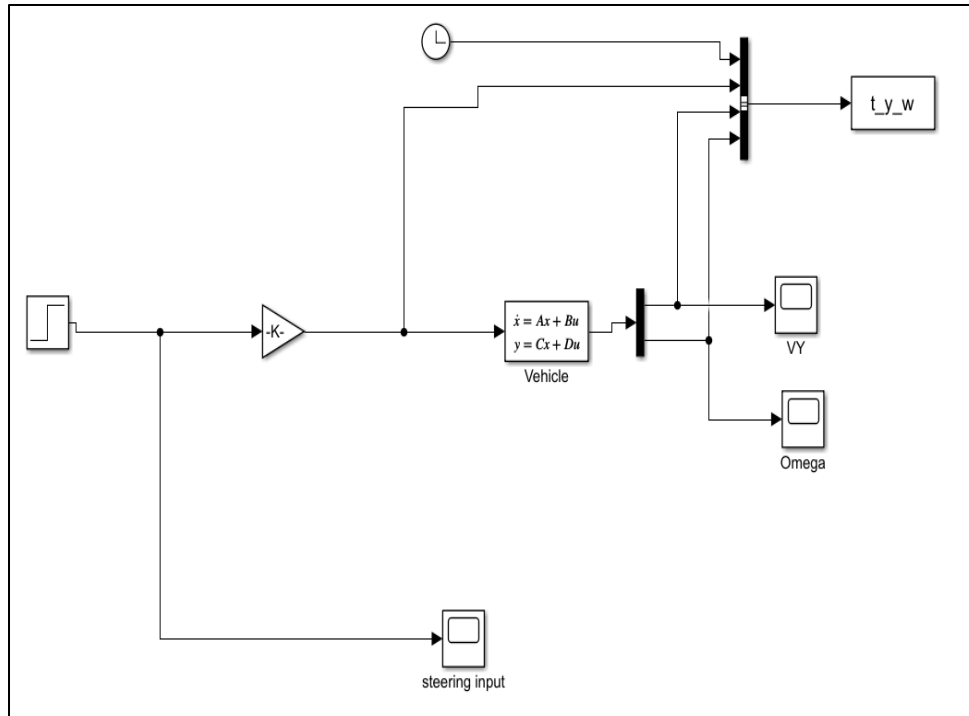


Figure (D-1)

Simulink open loop model representation.

(Appendix D-2)

MATLAB and Simulink model simulate closed-loop vehicle with disturbances

File name : vehiclegust.m

```
clear all
```

```
%handelig Characteristics open loop
```

```
%-----
```

```
W=19600; L=5.57; Lf=L/2; Lr=L/2;
Cf=30000; Cr=Cf;
g=9.81; Iz=2000;
Nsr=20;
Vx=100/3.6;
m=W/g;
```

```
A11=-(2*Cf+2*Cr)/(Vx*m);
A12=-Vx-(2*Lf*Cf-2*Lr*Cr)/(m*Vx);
A21=-(2*Lf*Cf-2*Lr*Cr)/(Iz*Vx);
A22=-(2*Lf^2*Cf+2*Lr^2*Cr)/(Vx*Iz);
```

```
B11=2*Cf/m; B21=2*Lf*Cf/Iz;
```

```
A=[ A11 A12; A21 A22];
```

```
B=[ B11 1/m 0; B21 0 1/Iz];
```

```
V=Vx*3.6
```

```
eig(A)
```

```
% iso path
```

```
% xc=30.5; % THE LONGITUDENAL DISTANCE (m)
```

```
% Lw=3.66; % THE LANE WIDTH (m)
```

```
% Tt=xc/Vx; % TIME ELAPSED TO COMPLETE THE LANE CHANGE  
(sec)
```

```
%
```

```
%
```

```
% t_step=0.001;
```

```
% tt=0:t_step:Tt;
```

```
%
```

```
%
```

```
% ttt=Tt+t_step:t_step:Tt;
```

```
% f_iso=-Lw.*(10*(Vx.*tt)./xc).^3-  
15*(Vx.*tt)./xc).^4+6*(Vx.*tt)./xc).^5);
```

```
%
```

```
% fttt=-Lw*ones(1,length(ttt));
```

```
% %f_iso_t=[tt',f_iso'];
```

```
%
```

```
% f_iso_t=[tt ttt]',[f_iso fttt]'];
```

Simulink file name: drivervehiclesim1.slx

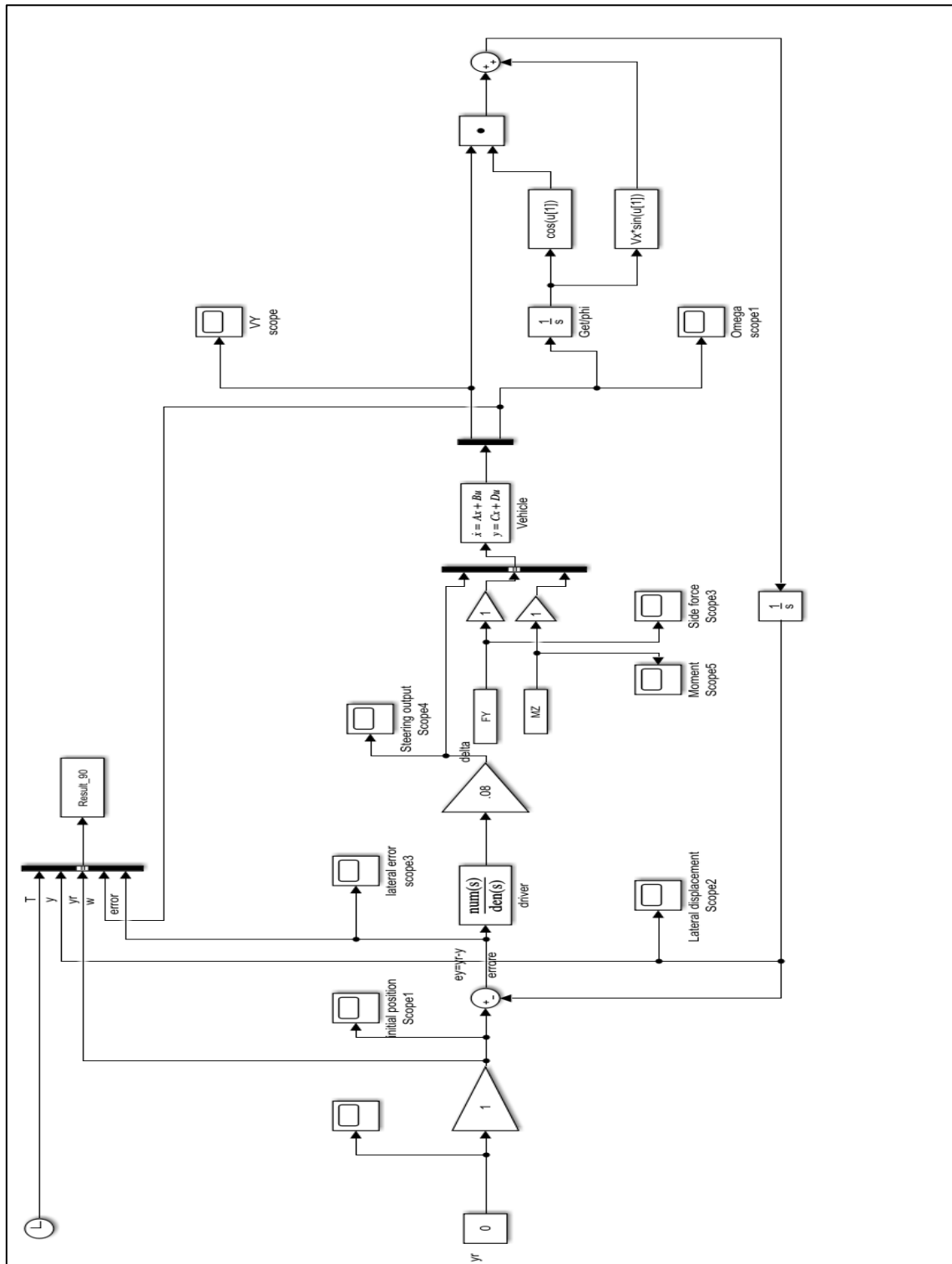


Figure (D-2)

Simulink close loop model representation with disturbances

Abstract (Arabic)

ملخص الرسالة

فيما يتعلق بالاستقرار الجانبي للمركبات الأرضية، فإن الديناميكا الهوائية في ظروف الرياح الجانبية المتغيرة السرعة (العاصفة) ، تتسم بأهمية متزايدة في عملية تطوير المركبات وكذلك تصميم وبناء الجسور. أثبتت الدراسات الأخيرة أن الأحمال الديناميكية الهوائية غير المستقرة يمكن أن تتجاوز الأحمال الثابتة بشكل كبير مما قد يؤدي إلى تدهور الاستقرار الجانبي للقيادة وقد يؤدي إلى فقدان التحكم. من أجل حساب وتقييم استجابة المركبة للرياح الجانبية المتغيرة السرعة، من الضروري تحديد تأثير الديناميكية الهوائية على جسم السيارة . تهتم هذه الدراسة بالثبات الديناميكي الجانبي للمركبات الأرضية أثناء المرور في ظروف الرياح المتقلبة الشديدة. في هذا البحث، يعتبر جسر الشيخ عيسى بن سلمان، نظرا لخواص البناء الهندسية الخاصة به فيما يتعلق بتوليد عصفات الرياح الجانبية، مثالا على ظروف الرياح المتقلبة. في أيام الرياح الشديدة، تتعرض السيارات لرياح عكسية متقلبة أثناء عبور الجسر. هذا يؤدي إلى شعور السائقين أنهم فقدوا السيطرة على سيارتهم. تم الإبلاغ عن وقوع عدة حوادث في الصحف المحلية تتعلق بحوادث فقدان المركبات للسيطرة الجانبية. وتركز هذه الدراسة على نمذجة المرور عبر الجسر المذكور للعثور على اختلافات نمط توزيع الأحمال الديناميكية للرياح لمختلف السرعات والاتجاهات، وتأثيرها على استقرار نظام تحكم ذو دائرة مغلقة لسيارة مع سائق.

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