Effects of Boundary Layer Scrapper on Aerodynamic Characteristics for Automotive Wind Tunnel Testing

Article history
Received
05 May 2015
Received in revised form
23 July 2015
Accepted
18 August 2015

I. A. M. Zali,[a] I. S. Ishak,[a,*]

[a] Department of Aeronautical, Automotive and Ocean Engineering,
Universiti Teknologi Malaysia,
Johor Bahru, Malaysia

*Corresponding author
shah@mail.fkm.utm.my

Abstract

The use of boundary layer scrapper for automotive wind tunnel testing has not yet been fully studied in the Universiti Teknologi Malaysia-Low Speed Tunnel (UTM-LST). The main purpose of this research is to study the influence of the boundary layer scrapper on an automotive wind tunnel testing at UTM-LST. The boundary layer scrapper chosen for this study is the vortex generator. To conduct this research successfully, an automotive wind tunnel model and three vortex generators have been fabricated for wind tunnel campaign in the UTM-LST. The frontal heights of the vortex generator are manipulated to test their effectiveness on scrapping the boundary layers on the wind tunnel test section floor. The aerodynamic characteristics of the automotive model aimed to be studied are the drag, lift, side force and yawing moment coefficients. Besides, qualitative study by tuft visualization has also been conducted to examine the flow reattachment lines due to use of different vortex generators. As conclusion from the findings, the use of boundary layer scrapper does affect the model's aerodynamic characteristics.

Keywords

Boundary layer scrapper; vortex generator; automotive wind tunnel testing; aerodynamic characteristics

Introduction

It has been centuries since the use of the wind tunnel testing began in the engineering field of work. Automotive aerodynamic characteristics have important effects on the dynamic property, economy, steering stability and comfortable property [1]. Wind tunnel functions as a simulator where a model of a solid object is placed in the test section. William H. Rae Jr. and Alan Pope [2] explained that near the end of the 19th century, a discovery led to the wind tunnel application where the model was held stationary and the air was moved past the model. There are two basic types of wind tunnels. The first basic tunnel type is an open circuit tunnel. The second basic type is a closed return wind tunnel (Prandtl or Gottingen type). More recently, wind tunnel has become an integral part of the automobile design and development cycle [3]. During wind tunnel tests, the relative motion between vehicle and road and the rotation of the wheels is often disregarded. The road is represented by the rigid floor of the test section, and the vehicle rests with stationary wheels on the pads of the balance platform. The boundary layer thickness near the model may reach half of ground clearance, which may affect the aerodynamic phenomenon around the car [4].

Boundary Layer Scrapper

Methods of simulating the moving road relative to a surface vehicle in a wind tunnel have been a vital subject of many researches in recent years. In the past, stationary vehicles were placed on wheel pads, flushed with the test section floor. The disadvantage of this configuration is the boundary layer profile that develops along the floor; by which the associated mass and momentum deficits alter the flow field compared to on-road experience. It is often possible to treat the flow past an object as a combination of viscous flow in the boundary layer and inviscid flow elsewhere. If the Reynolds number is large enough, viscous effects are important only in the boundary layer regions near the object. Outside of the boundary layer, the velocity gradients normal to the flow are relatively small, and the fluid acts as if it were inviscid [5].

Some commonly used boundary layer scrappers are tangential blowing, boundary layer suction, moving belt ground plane, vortex generator, and rotating wheels. In this study, the boundary layer scrapper chosen must be suitable for use and practical to be installed in UTM-LST, with intention to reduce cost.

Design And Fabrication

In this study, two things needed to be fabricated; a suitable boundary layer scrapper and an automotive wind tunnel model. Vortex generator was chosen as the boundary layer scrapper in this project because it is the easiest to fabricate and requires the lowest costs compared to the other boundary layer scrappers. Meanwhile, the selected automotive wind tunnel model was a Hyundai Veloster.

Vortex Generator

Vortex generator is well known in the aeronautical industry (on the tip of the wing) and in the automotive industry (on top of the car body). However, in this study, it is used to thin the boundary layer thickness in order to simulate a near real road condition. For this study, the vortex generator was made from aluminium sheets which were cut and bent according to the desired dimensions. The sheets were bent to 90^{o} where the vertical part would function to create some vortices from the windblown towards it, and the horizontal part would be attached to the test section floor. 3 different vortex generators, as listed in Table 1, were used in this experimental works to investigate their effectiveness on scrapping the boundary layers formed on the test section floor.

Table 1: Dimensions of Vortex Generator (VG)

VG	Frontal Height (mm)	Rear Height (mm)
VG 1	30	
VG 2	45	60
VG 3	15	

Fabrication of the Vortex Generator

Four aluminium sheets with thickness of 3mm were cut into required dimensions using Hydrabend cutting machine before being bent using the Akra folding machine. The only difference would be their frontal heights as the rear height of the vortex generators was kept constant at 60mm. Figure 1 and Figure 2 depict the fabricated vortex generators.

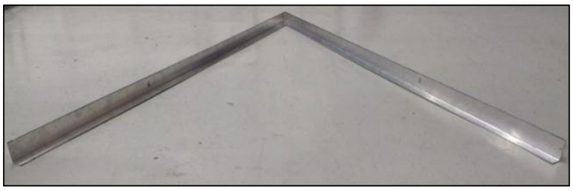

Figure 1: Vortex Generator 2 (45mm/60mm)

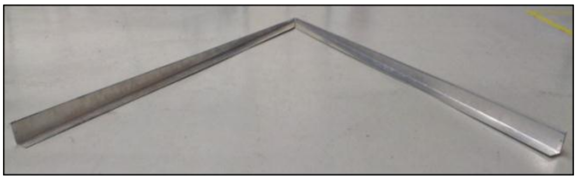

Figure 2: Vortex Generator 3 (15mm/60mm)

Fabrication of the Automotive Wind Tunnel Model

After numerous researches for the most suitable automotive model to be used in this study, Hyundai Veloster model was selected as it was the easiest to obtain its specific dimensions. A simplified generic wind tunnel model of Hyundai Veloster had been fabricated, where the original dimensions of the model were scaled down to 1:5 to fit the wind tunnel test section. The dimensions of the model are stated in Table 2.

Table 2: Rescaled dimensions of the model

Parameter	Dimension
Length	0.844 m
Width	0.358 m
Height	0.280 m
Frontal Area	0.087544 m^2

In the fabrication process, woods were attached together by using screws during the initial stage so that the parts could still be adjusted or removed if there were any differences in dimensions. Countersunk holes were made to provide some gaps for the screws to fully sink into the wood surface. After completing and combining the whole wooden model, some finishing processes were done before proceeding to undercoat process and surface painting. Figure 3 shows the fabricated model.

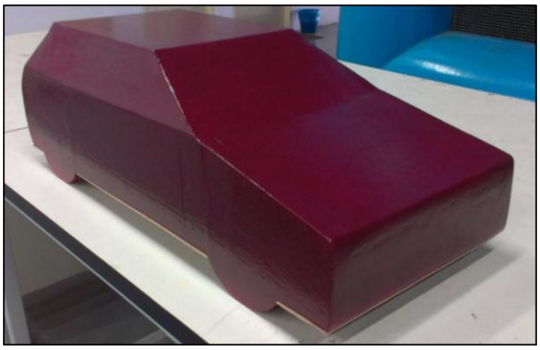

Figure 3: The simplified Hyundai Veloster wind tunnel model

Wind Tunnel Experiments

Wind Tunnel Test Set Up

The wind tunnel experiments were conducted in a 2.0m (width) x 1.5m (height) x 5.8m (length), closed-return wind tunnel at Aerolab, Universiti Teknologi Malaysia. The main objective of this test was to investigate the influence of the vortex generators on the Hyundai Veloster generic wind tunnel model in term of its aerodynamic characteristics. The main aerodynamic characteristics intended to be investigated were the coefficients of lift (C_L), side force (C_Y), drag (C_D) and yawing moment (C_N). The model was put at the centre of the test section turntable using a single strut support (Figure 4). Figure 5 depicts the model set-up inside the test section.

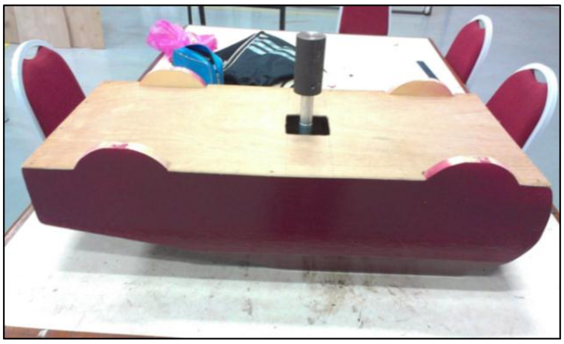

Figure 4: Single strut support

Reynolds Sweep test was conducted at wind speed of 10m/s, 20m/s, 30m/s, 35m/s, 40m/s and 45m/s to determine at what wind speed would the aerodynamic characteristics i.e. drag coefficient, become independent of the free-stream velocity. The following phases of tests were conducted at 40m/s and 15m/s according to the objectives of testing. All of the aerodynamic characteristics of the model were obtained from a precision six-component external balance located under the working test section.

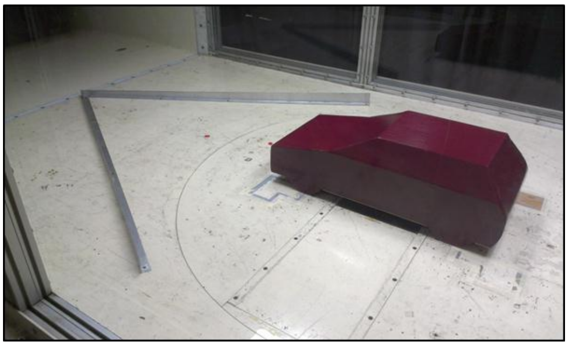

Figure 5: The positioning of the model and the vortex generator

Solid Blockage

Solid blockage is one of the blockage correction effects that needed to be determined in order to correct the uncorrected data collected from the experiment. For this research, the solid blockage was obtained from the effect of the model's maximum projected frontal area. The total frontal area of the model was then compared to the projected area from the wind tunnel test section (3 m^2). The solid blockage effect needed to be considered if the model's frontal area was between 1-10% of the test section area. If the percentage of area covered by the model was either less than 1% or more than 10% of the test section area, then the solid blockage correction would not be applicable.

$$\frac{Model's\ frontal\ area}{Test\ section's\ frontal\ area} = \frac{0.087544}{3} \times 100$$
$$= \mathbf{2.92}\%$$

The calculation proved that solid blockage correction needed to be performed to verify the wind tunnel results.

Wind Tunnel Data Correction

The aerodynamic loads collected from the six-component balance axis system were converted into standard aerodynamic coefficients in the wind axis coordinates system for an upright model.
The present model in the test section had its area through which the air must flow reduced. From the Continuity and Bernoulli's equations, this should increase the velocity of the air around the model. The forces and moments around the model became larger as the result of the air that sped up. Therefore, without any corrections applied, the aerodynamic coefficients would be overestimated. Therefore solid blockage correction must be applied. Calculation for drag correction is shown by Equation 1 [6].

$$C_D = C_{D\,(indicated)}\left(1 - \frac{2A}{S}\right) \quad (1)$$

Where:

A – Model frontal area
S – Wind tunnel cross section

Results And Discussion

Reynolds Sweep Test

Based on the result shown in Figure 6, the wind tunnel testing was decided to be conducted at 40 ms^{-1} since there were no gradual significant changes towards the aerodynamic coefficient because the coefficient was already independent of the wind velocity projected.

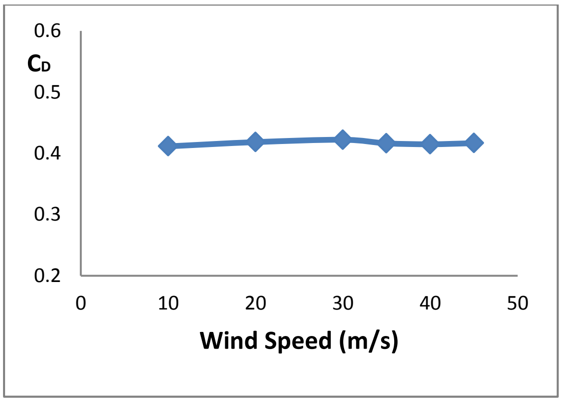

Figure 6: The graph of CD vs Wind Speed

Figure 7 shows the trend of aerodynamic drag towards wind speed. The drag force equation is given by formulation:

$$D = \frac{1}{2}\rho V^2 C_D \quad (2)$$

Based on the graph equation, it shows that the drag force was in a function of $V^{2.0319}$. The value was not perfectly '2' and might be due to some uncertainties occurrence during the experiment.

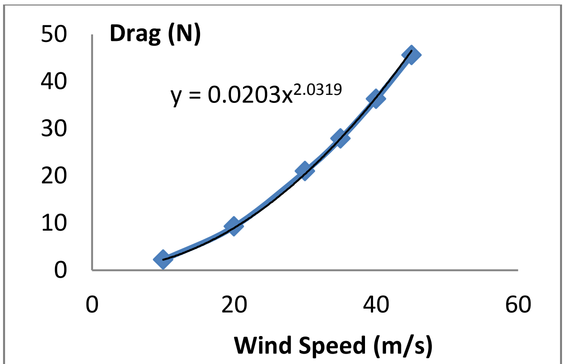

Figure 7: The graph of Drag vs Wind Speed

Coefficient of Drag

Figure 8 and Figure 9 show the drag coefficient characteristics towards yaw angles.

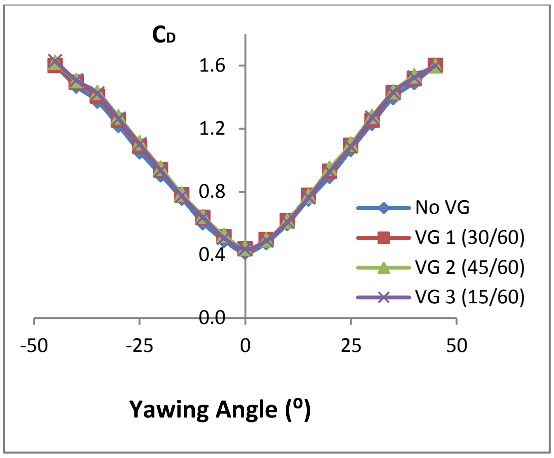

Figure 8: Comparison of CD at Various VGs

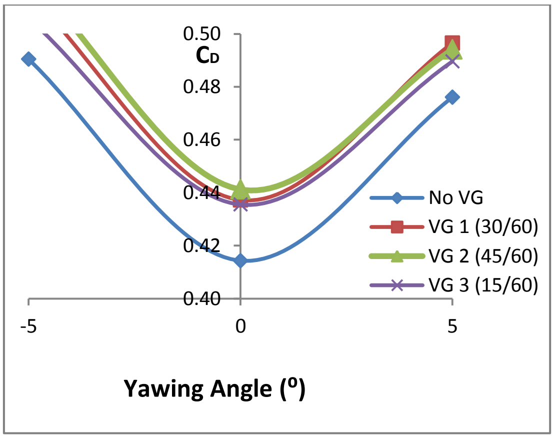

Figure 9: Close-up view of Figure 8 (Yaw Angle -5o to 5o)

Figure 9 concludes that different frontal heights of vortex generators proved to have produced some different results when tested. Listed below are the decreasing arrangement of drag coefficient values produced during each test using different types of VGs when the model was positioned at 0° yaw angle:

i. Vortex Generator 2 (45/60); C_D = 0.4412
ii. Vortex Generator 1 (30/40); C_D = 0.4373
iii. Vortex Generator 3 (15/60); C_D = 0.4355
iv. No Vortex Generator (No VG); C_D = 0.4144

Based on the results collected, the trend shows that with higher frontal height of the vortex generator, the drag coefficient produced on the model was greater. Hence, it can be assumed that the thinnest boundary layer was formed on the test section floor with Vortex Generator 2.

Coefficient of Yawing Moment

For this test, the model was yawed from angle of -45° to 45° with interval of 5°. The final collected data and data comparison earlier showed that the valid yawing moment data could only be taken from yaw angle of -25° up until 30°. All of the graphical data plotted showed a similar trend between one another, indicating that all of the collected data were valid and trustworthy.

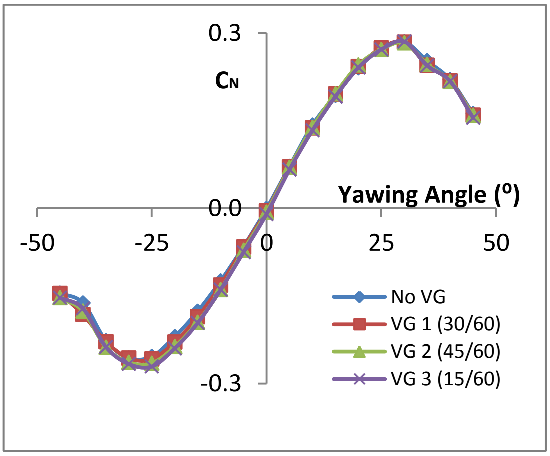

Figure 10: Comparison of CN at Various VGs

Figure 11 indicates that the model was well-built symmetrically, since the C_N value at 0° yaw angle was equal to 0 in all four VG configurations. It also provided an interesting information that the results of yawing moment from the wind tunnel testing were only acceptable from yawing angle ranging from -25° to 30° when using the vortex generators, while the results were acceptable from the yawing angle -30° to 30° for the case without vortex generator. This happened due to the turbulent flow produced once the wind hit the vortex generator and formed some reattachment lines, which will be explained in the following Sub-section 4.6.

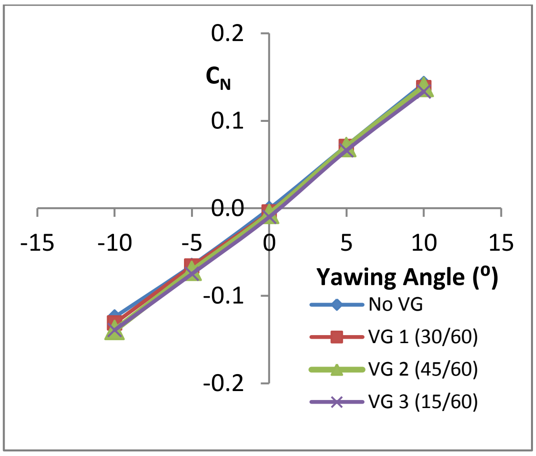

Figure 11: Closed-up view of Figure 10 (Yaw Angle -10 to 10o)

The yaw moment derivative was determined from the gradient of the yaw moment coefficient in the yaw angle range ±10°. The values are tabulated in Table 3.

Table 3: The yaw moment derivative

Testing	C_{N_ψ} (10° to -10°)
No VG	0.0134
VG1 (30/60)	0.0135
VG2 (45/60)	**0.0140**
VG3 (15/60)	0.0137

The data in Table 3 shows that the yaw moment derivative was highest when using VG2, followed by VG3, VG1 and lastly No VG. This shows that higher frontal of VG would contribute to higher yaw moment derivative.

Coefficient of Side Force

Figure 12 and Figure 13 show the results of side force coefficient characteristics towards yaw angles. The results depict a typical trend of automotive model.

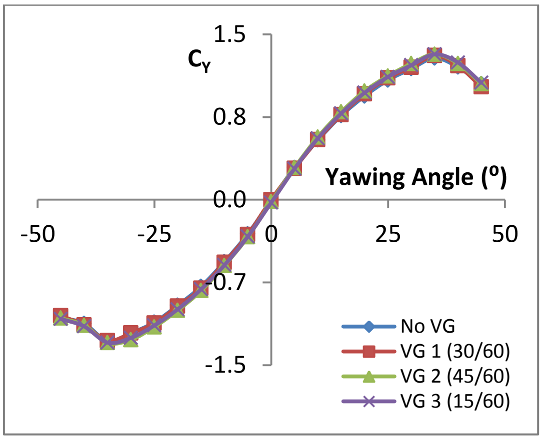

Figure 12: Comparison of Side Force Coefficient at Various VGs

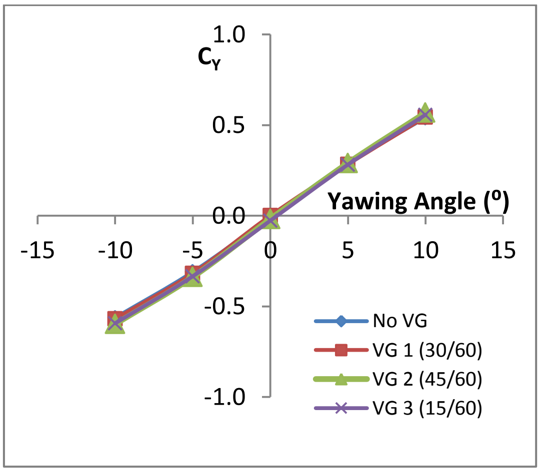

Figure 13: Close-up view of Figure 12 (Yaw Angle -10o to 10o)

The side force derivative was also determined from the gradient of side force coefficient in the yaw angle range ±10°, as tabulated in Table 4.

Table 4: The side force derivative

Testing	C_{Y_ψ}(10° to -10°)
No VG	0.0562
VG1 (30/60)	0.0566
VG2 (45/60)	**0.0592**
VG3 (15/60)	0.0583

Table 4 shares the same finding as Table 3, which indicates higher frontal of VG would contribute to higher aerodynamic derivative value.

Coefficient of Lift

Figure 14 illustrates that all graphs show almost the same trend, indicating that the use of vortex generators did not change the lift coefficient characteristics of this automotive model.

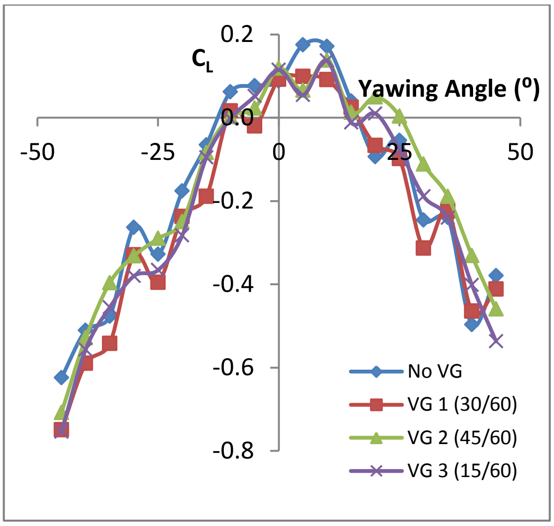

Figure 14: Comparison of Lift Coefficient at Various VGs

Reattachment Line

Qualitative tests had also been conducted to investigate the reattachment line of the flow when using the vortex generator.

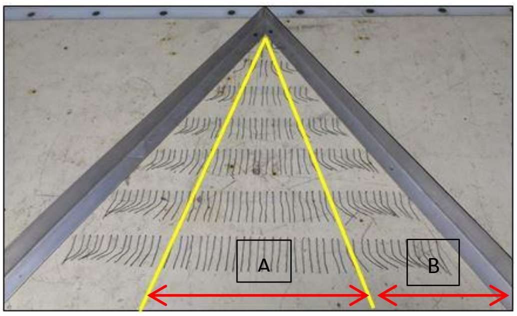

Figure 15: Flow Reattachment Line with VG 1 (30/60)

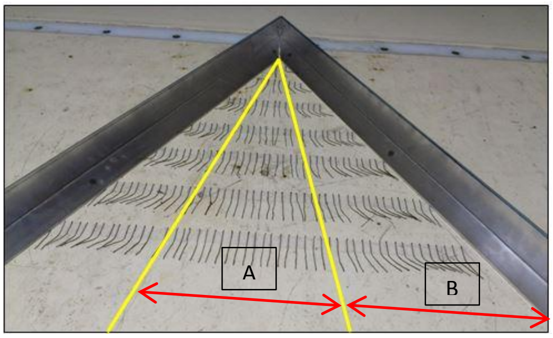

Figure 16: Flow Reattachment Line with VG 2 (45/60)

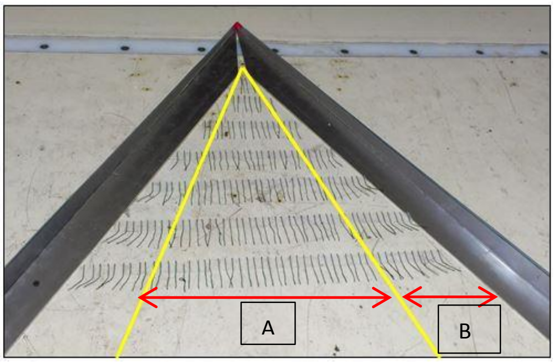

Figure 17: Flow Reattachment Line with VG 3 (15/60)

For this, wool tufts were stuck on the wind tunnel test section floor exactly behind the position of the vortex generator. The tests were conducted at wind speed of 15 ms^{-1} to observe the pattern of wool tuft. Figure 15 to Figure 17 show the qualitative results of the visualization tests for each VG configuration.

Table 5: Dimensions of the reattachment line

Vortex Generator	A (m)	B (m)
1 (30/60)	0.510	0.350
2 (45/60)	**0.440**	**0.385**
3 (15/60)	0.568	0.321

The V-shape lines drawn in Figure 15 to Figure 17 are the flow reattachment lines formed as the results of using the vortex generators. Test visualizations were conducted to compare the reattachment lines formed by each vortex generator. Vortices were created when the wind flow passed through the vortex generators, which eventually scrapped the initial boundary layers on the test section floor, consequently forming a thinner boundary layer. Leong [7] mentioned that reattachment line will move even far away from the vortex generators as the height of the vortex generator increases. The statement supports the results in Table 5, as VG2 showed the smallest value of **A** i.e. the reattachment line was the farthest from the vortex generator.

Conclusions

Wind tunnel tests for a simplified Hyundai Veloster generic model using three different vortex generators with different frontal heights (45mm, 30mm and 15mm) at wind speed of 40m/s and yaw angle ranging between -45° and 45° with interval of 5° have been successfully conducted. The results show that vortex generator does influence the aerodynamic characteristics of the tested model i.e. contributing to higher aerodynamic derivatives value. In addition, the findings are also tally as what has been predicted, in which with the use of vortex generator, C_D value will increase due to a thinner boundary layer thickness.

Apart of that, flow visualization test using wool tufts at wind speed of 15ms^{-1} has also been carried out and managed to furnish valuable information from the flow reattachment lines.

One of the aspects not given priority in this study is that the fabricated Hyundai Veloster model was a simplified model, where most of the aerodynamic curvatures on the body of the model had been removed due to lack of fabrication skills and time constraint to finish the project. Therefore, it is acknowledged that the aerodynamic coefficients obtained in this test may slightly differ from the ones of the actual Hyundai Veloster.

Acknowledgements

Authors would like to thank Aerolab Team of Universiti Teknologi Malaysia for their technical support during the wind tunnel testing.

References

[1] *Jingyu, W. and Xingjun H., 2012. Applied Mechanics and Materials Vols 170-173 (2012) pp 3324-3328 Online: 2012-05-14 © (2012) Trans Tech Publications, Switzerland.*

[2] *William H., Rae Jr. and Alan P., 1984. Low-Speed Wind Tunnel Testing. Second Edition. Toronto, Canada: John Wiley & Sons, Inc.*

[3] *Hucho, W.H. and Sovran, G., 1993. Aerodynamics of Road Vehicles. Annual Rev. Fluid Mechanics.*

[4] *Willemsen, E., Pengel, K., Holthusen, H. and Albert K., 2011. Automotive Testing in the German-Dutch Wind Tunnels. New Trends and Developments in Automotive Industry. Rijeka, Croatia: InTech Europe.*

[5] *Munson, B.R., Donald F.Y., Ted H.O. and Wade W. H., 2010. Fundamental of Fluid Mechanics (6th ed.) John Wiley & Sons (Asia) Pte Ltd.*

[6] *Barnard, R.H., 1996. Road Vehicle Aerodynamic Design, Addison Wesley Longman Limited.*

[7] *Leong, S.C., 2003. Boundary Layer Measurement for UTM-LST. Bachelor of Mechanical-Aeronautics Engineering, UniversitiTeknologi Malaysia.*