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ABSTRACT

For any high performance vehicle the aerodynamic properties are significant when attempting to optimize performance. For ground vehicles the major aerodynamic forces are drag and down-force. The focus of this research was to determine the feasibility of vortex generation as a method to reduce the aerodynamic drag of a racing class motorcycle.

Wind tunnel tests were performed on a full-scale racing motorcycle in the Closed Loop Tunnel (CLT) at West Virginia University (WVU) and in Old Dominion University's (ODU) Langley Full Scale Tunnel (LFST) at various airspeeds. Counter-rotating vortices were generated using small commercially available vortex generators (VGs).

The largest reduction in drag was 10%, which was measured in the WVU CLT. The LFST tests showed no measurable increase or decrease in drag. This led to the conclusion that the airspeed and test section blockage ratio influenced the optimum configuration and size of the vortex generators. This preliminary research shows that the use of small vortex generators can reduce the overall drag.

INTRODUCTION

To improve performance of a racing-class motorcycle one option is to reduce the aerodynamic drag. The drag can be reduced through either an overall redesign of the exterior shape or through some type of flow control mechanism. Due to the limitations imposed on the length of the motorcycle set by race officials, and due to the constraints of the racing circuit, significant changes to the shape of the fairings are not practical. Therefore one of the more practical choices for drag reduction is to use flow control techniques aimed at reducing the flow separation effect and size of the wake of the motorcycle.

There are several different types of flow control devices including vortex generation, suction or a blowing jet. The use of either blowing jets or suction has an added penalty of the additional power required to perform these tasks. On the other hand, using vortex generation requires minimal additional power. It is proposed that if these VGs are properly aligned and placed, they have the potential to reduce the drag. Multiple types of vortex generating devices exist; they range from strategically located metal vanes that induce small vortices to a dimple tape that introduces turbulence into the boundary layer.

For this preliminary investigation, it was determined that the metal, counter-rotating vortex generating vanes would be used as the flow control device for this research. Testing was conducted in multiple phases between the WVU Closed Loop Wind Tunnel (WVU CLT) and the Langley Full Scale Tunnel (LFST). All of the testing was conducted with no tire rotation and on a stationary ground plane with the model elevated out of the boundary layer of the ground plane. Since the primary concern was a relative drag difference, the ground simulation techniques had minimal effect on the results of this research.

For this testing, a full-scale motorcycle was used as the model. In the WVU CLT there was a blockage ratio of 0.208. This high blockage ratio led to the testing of an increased blockage case in the WVU CLT, and the testing conducted at the LFST. It was determined that wind tunnel blockage had a considerable effect on the aerodynamics of the VGs. This is important to know since during the course of a race the clearance of the fairing with other objects can emulate blockage effects, including side-by-side racing and steep banking of the motorcycle.

Despite the infringement of tunnel walls on the dynamics of a vortex generator, it was found that vortex generators could effectively reduce the drag. Phase I of testing, conducted at WVU, resulted in a maximum drag reduction of 118 drag counts (10.1%) from the baseline, or an increase of up to 355 drag counts (30.5%), depending on the placement. The results from Phase II, testing at LFST, showed no significant reduction or increase in the drag coefficient, but only limited testing was conducted. The VGs produced a reduction of 48 drag counts (7.8%) and an increase of 217 drag counts (35.2%) for Phase III tests, again at WVU. Therefore, it is possible to use vortex generators to reduce the drag on a motorcycle. However, the configuration of these vortex generators that can provide the maximum drag reduction in a real scenario (full scale Reynolds numbers; with tire rotation and moving ground plane) was not the subject of these tests.

GENERAL DRAG REDUCTION

In general, the drag experienced by a ground vehicle is dependent on the exterior shape and the cross sectional area of the vehicle. According to Hucho (1998) car-like basic bodies of very low drag (C_D = 0.15) have been developed and used in some concept car designs. But, these low-drag research bodies have not been implemented into production cars, which have a current drag coefficient of approximately 0.30. Starting from a free-flying body, low drag bodies have three factors that increase the drag: the effects of camber, thickness and for truncated bodies, the base pressure in the wake region.

The lower limit of basic ground vehicle bodies is in the range of 0.07 to 0.09, according to Hucho. However, when adding the wheels the drag coefficient increases to 0.14 to 0.16. Therefore, to further reduce the vehicle drag the airflow underneath the car and around the wheels needs to be improved. Another method of reducing the drag is using a higher length to height ratio. Increasing the length is not always the best solution for a production vehicle due to practicality issues.

Less conventional methods of reducing the drag on a ground vehicle include base bleed, re-energizing the wake of the vehicle and reducing the effective base area. The base bleed concept channels to cooling air for the engine to the rear of the vehicle, partially filling the wake and increasing the base pressure of the vehicle. The cross section of the base of the vehicle can be reduced through the use of the jet or slot blowing. This effect is generated when high-speed air is injected at the lower and upper edges of the rear of the vehicle, which allows the flow to remain attached longer, increasing the base pressure. The wake of the ground vehicle can also be reduced through the use of spoilers, which deflect the airflow toward the centerline of the wake region. This effect may also be achieved with properly placed vortex generators.

TIRE ROTATION AND GROUND SIMULATION

Two questions that need to be addressed in any ground vehicle wind tunnel testing are simulating the ground beneath the vehicle and whether or not the tires need to be rotated during testing. Since this research investigates relative drag differences, it was determined to use a non-rotating wheel and that the model would be elevated out of the boundary layer of the test section floor, approximately 1/4 inch. Future testing would investigate these concerns and determine the need to better simulate the real world conditions.

Testing performed by Cogotti (1983), as well as Stapleford and Carr (1970) compared the effects of a rotating wheel for open-wheeled automobiles, which has some similarities to the motorcycle tires. It was found that there was a 5 drag count difference between the rotating and non-rotating case. Carr (1994) suggests that the power required to operate a ground plane suction device is not beneficial for the minimal improvements in the reality of the simulation. Mercker and Wiedemann (1990) looked at the benefit of using a rotating floor in automotive testing. Beauvais, et al (1978), as well as Ashill (2001), compared different ground simulation techniques. These results, shown in Table 1, led to the use of the elevated model.

Table 1: Summary of Test Results from Beauvais, et al (1978).

	C_L	Variation (%)	C_D	Variation (%)
Full Scale Vehicle	0.552	----	0.540	-----
Fixed Ground Plane	0.596	8.0	0.548	1.5
Moving Belt Ground Plane	0.417	-24.5	0.510	-5.6
Fixed Ground Plane Model at 0.125 in	0.570	3.3	0.553	2.4

WIND TUNNEL BLOCKAGE

In wind tunnel testing, it is important to consider the size of the model to be tested with respect to the size of the test section. There is a trade off that needs to be made when performing wind tunnel tests; one side of the argument is to reduce blockage as much as possible. The other is to increase model size for scale issues, more accessibility for instrumentation, etc. Not only is the physical size of the model important, but so is the size of the wake created by the model. According to Barlow, Rae and Pope (1999) it is also important to consider the momentum effects outside the wake, when separated flow is present. These effects are produced by a lateral-wall constraint on the wake and results in a lower wake pressure, which in turn produces a lower base pressure on the model than would occur in free air. The standard parameter in discussing the size of the model is the blockage ratio, which is defined as the ratio of the model frontal area over the test section cross sectional area. Typical blockage ratios used are 0.05, 0.10, and 0.20 in some cases. However Katz and Walters (1995) suggest avoiding a blockage ratio that is higher than 0.07.

Some corrections for wind tunnel blockage can be formulated, but they merely provide some estimation of the wall effects. Additional effects, such as an altered boundary layer transition, turbulence levels, and deforming streamlines may also exist.

One effect of test section blockage is an increase in air speed through the narrowed passage between the model and the walls. The increased speed artificially raises the values of the aerodynamic coefficients. This discrepancy is difficult to measure because of the desire to avoid disturbances, such as pitot-static tubes, in the airflow close to the model. In high blockage ratio testing the interaction between the walls of the test section and the model surface result in effects similar to ground effects experienced in aircraft testing. Several mathematical formulas have been developed to account for test section blockage in the measurement of drag.

The following corrections for drag coefficient were formulated by Barlow, Rae and Pope (1999) where C_D is the corrected drag coefficient, C_{Dmeas} is the measured drag coefficient, A is the model frontal area, S is the cross sectional area of the test section, and C_{Pmin} is the minimum pressure on the model.

$$C_D = \frac{C_{D_{meas}}}{\left(1 + \frac{A}{4S}\right)^2} \qquad (1)$$

$$C_D = \frac{C_{D_{meas}}}{\left(1 - C_{P_{\min}}\right)} \qquad (2)$$

EXPERIMENTAL APPARATUS

Dr. Robin Tuluie, designer of the Tul-Aris motorcycle (Tuluie, 2000), provided a full-scale model of the motorcycle for this project. The model consists of a hand built metal frame, which holds the actual racing fairings of the 2001 Tul-Aris in their proper position and a dummy rider wearing all the proper racing gear (leathers, boots, gloves and helmet). The fairings are composite structures with a smooth surface; there was a small portion of racing damage on the left side of the lower fairing. This damage was repaired using body putty. It was determined that this minor damage would have little effect on the results since a relative drag difference was the primary concern.

It was noticed during Phase I of testing that the lower fairing of the model had a considerable amount of movement while air was flowing over it. After completion of Phase I a second support was added to the lower fairing, which alleviated most of the vibrations during testing. The stiffened model was then used for Phases II and III.

When deciding what type of vortex generator to use, several types were considered including: sail type, forward and backward wedges and counter-rotating vanes. From testing conducted by Ashill (2001) it was determined that the use of the counter-rotating pair of vanes created the highest circulation and therefore was more desirable to use in this application. The shape used was developed and presented in Wheeler (1991).

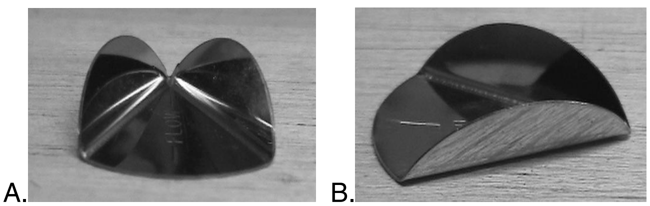
A.  B.

Figure 1: 1/2-inch Vortex Generator used.
A. Front View B. Side View

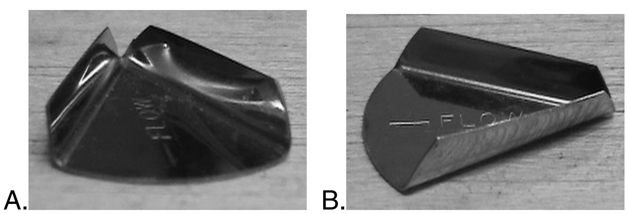
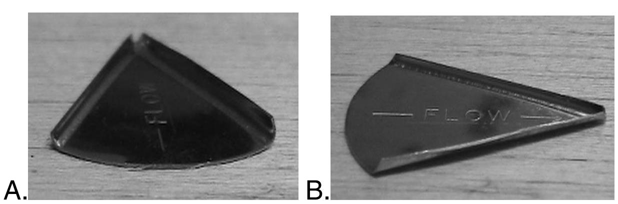
A.  B.

Figure 2: Modified 1/4-inch Vortex Generator.
A. Front View B. Side View

A. 

B.

Figure 3: Modified 1/8-inch Vortex Generator.
A. Top View B. Side View

A blockage ratio of 0.208 was present during testing in the WVU-CLT test section. After adjusting the velocity for blockage the coefficient of drag does not adequately agree with the Langley Full Scale Tunnel testing. Therefore the Barlow, Rae and Pope (1999) method of accounting for blockage in wind tunnel testing, as in the Equation 1, was used to account for this high blockage ratio.

Similarly, the type of ground simulation technique used in this testing was determined to be the use of the stationary tunnel floor with a slightly elevated model, approximately 1/4 inch from the tunnel floor. This was found to be the best option due to the limited cost and simplicity in installation. According to Beauvais, et. al. (1978), Table 1, this would result in a variation of approximately 3% in the lift and drag components. Again, the ground simulation conditions are constant between tests so the measured change in drag is not a result of the ground simulation technique used during testing. However, effects of the non-rotating wheel on the vortex generators can not be quantified at this time.

Three types of measurements were taken during the testing at West Virginia University: drag force, air temperature and surface pressure at various locations. The primary measurement, drag force, was recorded through an Omegadyne S-Type Load Cell with a range of 25 lbs. Due to the tendency of the temperature for the air in the wind tunnel to increase, a Type J thermocouple was used to measure the rise in temperature and account for the changes in the density of the air. The model surface pressure measurements were taken using a Scanivalve system that incorporated a single pressure transducer, with a range of 1 psid and the ability to measure up to 48 pressure taps sequentially. Using a system built at WVU the pressure transducer was calibrated by applying a pressure to both the water manometer and the Scani-Valve using a vacuum pump then sealing the system with a valve. After incrementing the pressure back to atmospheric pressure the calibration was complete. These three devices all produce a voltage output, which enabled the use of a computer-based data acquisition system with a 12-bit data acquisition card.

To better determine the velocity of the airflow along the side of the model a pitot-static tube was installed between the model and the tunnel wall for several test cases. This flow measurement device was placed near the location of maximum thickness of the model and connected to a manometer to determine the velocity of the air. This test was conducted for both the original blockage ratio of 20.8 % and the increased blockage of 21.5 %. Increasing the blockage provided some insight into the effects the wall had on the vortex generators and the corresponding effect on the overall drag force.

With the assistance of Old Dominion University, the Tul-Aris model was installed and tested in the Langley Full-Scale Wind Tunnel. In this test section the blockage ratio was 0.002, which is well within the accepted standard of a blockage ratio of less than 0.07 according to Barlow, Rae and Pope (1999). The LFST is equipped with an automobile force balance used for the testing of cars. A sting mount was designed and built for the motorcycle, which was installed in the 40ft x 60ft test section of the LFST. A pressure transducer was also used to measure the surface pressure along the 38 static pressure taps during testing. Existing Labview codes on the LFST control room computers were used for data acquisition.

Due to the lack of experience and empirical knowledge of vortex generators, the placement of these devices is essentially trial and error. To better visualize the location(s) of separation and thus placement of the vortex generator(s), the initial test was a tuft visualization test. Once the locations of flow separation were determined, the vortex generators were gradually added to the model in a symmetrical fashion just upstream of the observed separation point location. The vortex generators were attached to the motorcycle using standard dual temperature hot glue, which can be scraped from the surface.

Knowing the locations in which the flow separated, it was determined that the vortex generator would be placed slightly upstream of the separation. However, this would mean that the configuration depends on the airspeed, since as the airspeed increases the separation location moves forward. It was decided that testing would be done in a gradual process, starting with three VGs, one along the centerline of the bike and a symmetric pair of VGs on the trailing edge of the upper fairing. Additional symmetric pairs of VGs were then added until vortex generators addressed the majority of locations of separated flow.

EXPERIMENTAL PROCEDURE

Testing for this research was performed in three phases. Phase I was conducted in the Closed Loop Wind Tunnel at West Virginia University, and consisted of three vortex generator heights and five VG configurations. After the previously mentioned modifications to the model two configurations for each VG size were tested in Phase II at the Langley Full Scale Tunnel. Phase III, in the WVU CLT, retested the configurations from Phase II as well as parametric studies on the upper and lower fairings.

After collecting data the following steps were used to reduce the data to a drag coefficient for comparison. To calculate the drag force measured during Phase I of testing the velocity was adjusted for the reduced area caused by the test section blockage. The following equation was used to adjust the velocity, where V_{act} is the actual velocity along the sides of the model, V_{meas} is the measured free-stream velocity, $A_{T.S.}$ is the test section cross-sectional area and A_{fr} is the model frontal area.

$$V_{act} = V_{meas} \frac{A_{T.S.}}{\left(A_{T.S.} - A_{fr}\right)} \qquad (3)$$

The drag coefficient of the motorcycle was determined through the use of the equation shown below, where C_{Dm} is the drag coefficient of the model, D_{meas} is the measured drag force, A_{fr} is the frontal area of the motorcycle.

$$C_{D_m} = \frac{(D_{meas})}{\frac{1}{2}\rho V^2 A_{fr}} \quad (4)$$

The average drag coefficients were calculated for each test configuration for comparison purposes. The average values were then compared to the baseline average in terms of percent difference. All experimental measurements have some associated error. It is important to know the level of this error when analyzing results. A propagation of error technique was used to determine the error in the calculated dependent variable, drag coefficient, $C_{D.}$ This value is dependent upon the four measured variables: drag force, *D*, the pressure, *P*, temperature, *T*, and the airspeed, *V*. Equation 5 is used to calculate the uncertainty in the drag coefficient. The errors in the instrumentation used during testing are listed in Table 2.

$$\delta C_D = \left[\left(\frac{\partial C_D}{\partial D}\delta D\right)^2 + \left(\frac{\partial C_D}{\partial P}\delta P\right)^2 + \left(\frac{\partial C_D}{\partial T}\delta T\right)^2 + \left(\frac{\partial C_D}{\partial V}\delta V\right)^2\right]^{\frac{1}{2}} \quad (5)$$

Table 2: Bias errors for measuring devices used in WVU CLT tests.

Instrument	Error
Omegadyne load cell	±0.03 %
Scani-Valve Pressure Transducer	±0.5 %
Omega Type-J Thermocouple	±0.20 °C

VORTEX GENERATOR CONFIGURATIONS

Due to time constraints, it was determined that five different vortex generator configurations were to be tested in Phase I, each of which would add a pair(s) of symmetric VG's to the previous test. Testing was also completed for VG heights of 1/8", 1/4" and 1/2", here after referred to as VG3, VG2, and VG1, respectively. The progression of tests started at the baseline configuration with no vortex generators on the motorcycle. In the first vortex generator configuration a VG to added to the helmet of the rider and a pair of VG's on the upper fairing. The next configuration adds a pair of VG's on the upper fairing to interact with the airflow over the handlebars of the motorcycle, Configuration 2.

Configurations 3 and 4 both add VG's to Configuration 2. Configuration 3 adds two pairs of VG's at the trailing edge of the lower fairing, while Configuration 4 places these two pairs of vortex generators just upstream of the location of maximum thickness of the lower fairing. Each of these configurations was tested 3 times to produce an average value for comparison with the baseline results. Configuration 5 adds a pair of vortex generators to the lower fairing along the maximum thickness, 3 pairs of VG's to the leading edge of the lower fairing and 2 pairs to the upper fairing along the trailing edge so they are spaced 4 inches apart. Hence when the nomenclature VG1C3 is referred to, the test being discusses is the 1/2" vortex generator orientated as in configuration 3 described above.

Five modified vortex generator configurations were then tested. The first modified run moved the pair of VG's located near the front wheel to the ends of the handlebar. Modification 2 moved the vortex generators on the upper fairing forward 1 inch. Next, the forward three pairs of VG's on the lower fairing were moved back an inch. The fourth modified configuration moved the VG's nearest the riders' shoulders toward the centerline of the motorcycle by a distance of one inch. The fifth and last modified configuration moved the vortex generators forward an additional inch.

Several of the previously described configurations were repeated in Phase II and Phase III. In addition, Phase III added an "O" preceding the descriptor and had two parametric studies conducted. The parametric study on the upper surface (OVG3P) with 4 pairs of vortex generators started at the trailing edge with a small increase in drag and worked toward the leading edge. Parametric Position Number 3, which was approximately 10 inches from the leading edge recorded the greatest reduction in drag coefficient of these four tests.

A similar parametric study was conducted on the lower fairing (OLFP) with 3 pairs of VG's was tested at three locations starting at the leading edge. These tests all show a reduction in relative drag coefficient, from moving the VG's upstream it was noticed that the position near the center of the lower fairing showed the largest drag reduction. It was expected that the VG size should be smaller than the boundary layer thickness, which is supported by the data where near the leading edge of the fairing there is a smaller reduction in drag. The decrease in drag reduction further downstream can be explained by the increased thickness in the boundary layer making the VG less effective by reducing the ratio of VG height to boundary layer thickness. Therefore, it is best to place the VG where its height is approximately the boundary layer height, or slightly smaller than the boundary layer.

RESULTS

Wind tunnel testing was conducted in three phases between the WVU Closed Loop Wind Tunnel and the Langley Full Scale Tunnel operated by Old Dominion University. Phase I of testing was conducted in the WVU Closed Loop Wind Tunnel. During the first phase of testing considerable vibration was noticed in the lower fairing of the model. Therefore, an additional stiffener was added to the model. The results from Phase I were used to reduce the number of configurations tested in Phases II and III. Figure 1 shows the average relative change in drag coefficient, from the baseline value of 1.163, for the 20 configurations tested in Phase I. The error bars displayed in this figure illustrate instrumentation error for the drag coefficient, determined to be ±0.007. The most promising configurations for drag reduction were found to be those with the 1/8-inch vortex generator. These results are also tabulated in Table 3 with the relative change in C_D (ΔC_D) displayed as well as the standard deviation of the measurement. There is no standard deviation for the last five entries in the table because there was only one test measured with that particular configuration.

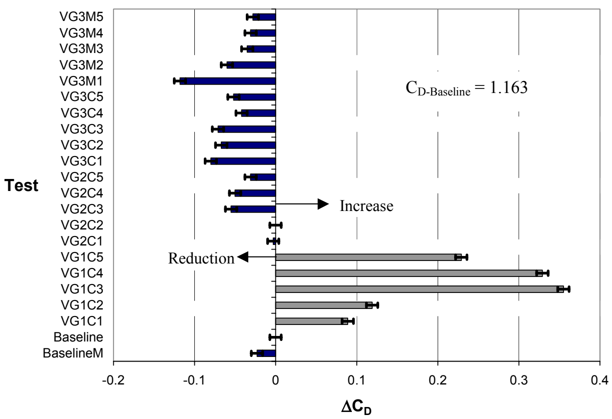


Figure 4: Comparison of Relative Drag Coefficients for Phase I of Testing Conducted in the West Virginia University Closed Loop Wind Tunnel.

Table 3: Measured Change in Drag Coefficient and the Standard Deviation of the Measurement for Phase I of Testing.

Test	ΔC_D	STDEV
BaselineM	-0.014	0.0064
Baseline	0	0.0267
VG1C1	0.089	0.0739
VG1C2	0.119	0.0883
VG1C3	0.355	0.0195
VG1C4	0.329	0.2014
VG1C5	0.229	0.2793
VG2C1	0.003	0.0150
VG2C2	0.000	0.0083
VG2C3	-0.055	0.0242
VG2C4	-0.050	0.0172
VG2C5	-0.031	0.0128
VG3C1	-0.080	0.0219
VG3C2	-0.067	0.0231
VG3C3	-0.071	0.0126
VG3C4	-0.042	0.0065
VG3C5	-0.052	0.0054
VG3M1	-0.118	-------
VG3M2	-0.060	-------
VG3M3	-0.035	-------
VG3M4	-0.031	-------
VG3M5	-0.028	-------

The effect of the vortex generator height on drag reduction was determined during Phase I. Figure 2 shows the effects of VG height on the drag coefficient for VG Configuration 4. For all configurations it was determined that the general trend was that as the height of the VG increases its ability to reduce drag decreases. For comparison purposes the change in drag coefficient, ΔC_D, is simply the difference between the drag coefficient for that test and the average of the baseline configurations. It is important to note that this optimum height will change for any change in speed and possibly blockage ratio, since it is dependent upon the boundary layer thickness. It is believed that the effectiveness of the VG is diminished if the height of the device is allowed to protrude through the boundary layer.

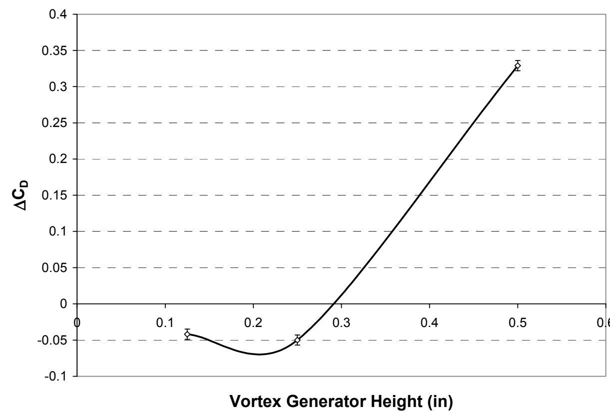


Figure 5: Effects of Vortex Generator Height on Configuration 4 during Phase I testing.

The modified baseline configuration (BaselineM) was taken after removing the radiator simulation from the model. In addition, there was a 14 drag count reduction in the drag coefficient as well as a decrease in the standard deviation of the measurements. It is important to note that the modified baseline from Phase I is the baseline configuration for Phase II and III.

Testing conducted in the Langley Full Scale Wind Tunnel with the cooperation of Old Dominion University for Phase II had marginal results, which was primarily due to the limited time and high cost of testing in the LFST. In the time allotted blockage effects were the first consideration. More testing time in this facility would be needed to determine a drag reducing VG configuration. As seen in Figure 3 most configurations showed a drag increase, and those with a drag decrease were within the instrumentation error (±2% of C_D). The actual values of the drag coefficient and each configuration change from the average baseline drag coefficient are listed in Table 4 for the 55 ft/s case. Table 5 covers the C_D and ΔC_D values for the 70 ft/s, and the 120 ft/s case are listed in Table 6. Again, there are only marginal changes in the drag coefficient for Phase II testing at all three airspeeds.

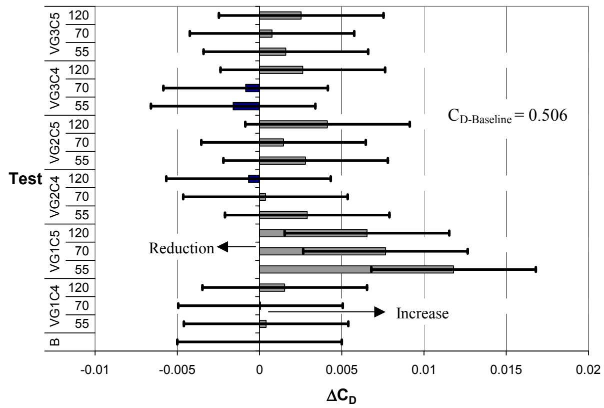


Figure 6: Comparison of Relative Drag Coefficients for Phase II of Testing, Conducted in the Langley Full Scale Wind Tunnel.

Table 4: Drag Coefficients of the 55 ft/s tests Conducted in the LFST, Phase II.

Test	C_d	$\Delta\ C_d$
Baseline	0.5051	--------
Baseline2	0.5072	--------
VG1C4	0.5062	0.0004
VG1C5	0.5176	0.0118
VG2C4	0.5087	0.0029
VG2C5	0.5086	0.0028
VG3C4	0.5042	-0.0016
VG3C5	0.5074	0.0016

Table 5: Drag Coefficients of the 70 ft/s tests Conducted in the LFST, Phase II.

Test	C_d	$\Delta\ C_d$
Baseline	0.5067	--------
Baseline2	0.5048	--------
VG1C4	0.5056	0.0001
VG1C5	0.5132	0.0077
VG2C4	0.5059	0.0004
VG2C5	0.5070	0.0015
VG3C4	0.5047	-0.0008
VG3C5	0.5063	0.0008

The dependence of the drag coefficient on the airspeed for the baseline tests is shown in Figure 4. The differences in the drag coefficient measured for these tests falls within the 2% error in the measurements, which is shown by the error bars on the plot. Figure 5 shows the velocity dependence of the 1/8-inch VG for the two configurations that were tested in the LFST. Again, the difference in the drag coefficient is within the instrumentation error for both the speed dependence and the configuration change. The authors believe that given more time, a VG configuration could have been found (height and placement) that produced a drag reduction. It appears that the VG configuration to produce drag reduction in blocked flow is different than that required for free airflow. This could have implications for a racing-class motorcycle operation in a close group or banked in a turn. vortex generator increases the drag coefficient over the baseline configuration. Similarly, the 1/4-inch VG increases the drag coefficient but Configuration 5 has only half the increase of Configuration 4. Unlike the Phase I results the drag coefficient for two of the 1/8-inch VG configurations experienced a small drag increase; possible causes of this are discussed in the Conclusions.

Tests for Phase III were conducted in the WVU Closed Loop Wind Tunnel. Figure 6 shows the average measured change in drag coefficient for the 12 tests conducted for each configuration during this phase of testing. From this figure it is seen that the 1/2-inch

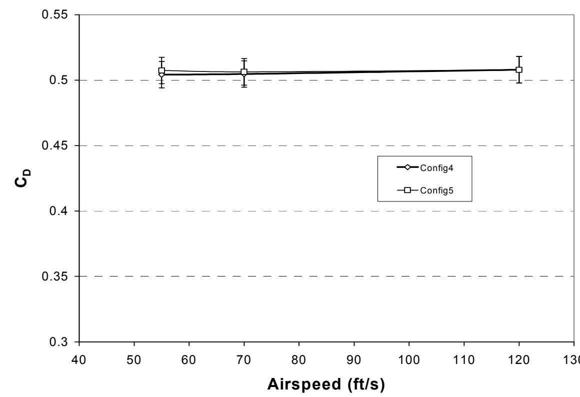


Figure 7: Variation in Drag Coefficient with Free stream Velocity for the Phase II Baseline Configuration.

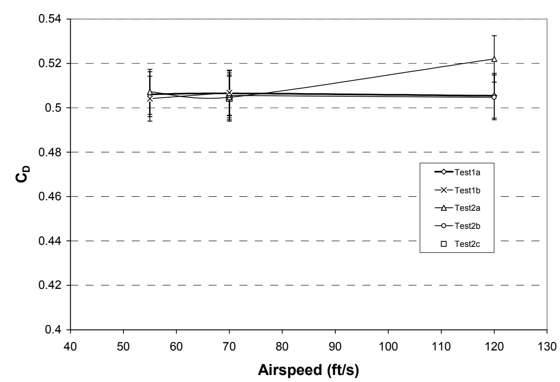


Figure 8: Variation in Drag Coefficient with Free stream Velocity for the Phase II 1/8-inch Vortex Generator Configurations 4 and 5.

Table 6: Drag Coefficients of the 120 ft/s tests Conducted in the LFST, Phase II.

Test	C_d	$\Delta\ C_d$
Baseline	0.5054	--------
Baseline2	0.5054	--------
VG1C4	0.5069	0.0015
VG1C5	0.5119	0.0065
VG2C4	0.5047	-0.0007
VG2C5	0.5095	0.0041
VG3C4	0.5080	0.0026
VG3C5	0.5079	0.0025

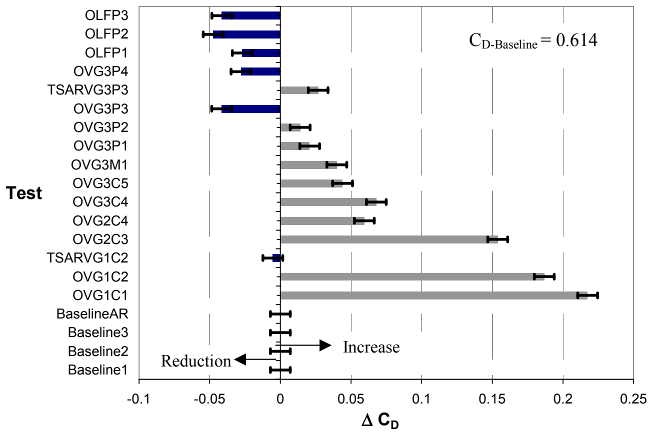


Figure 9: Comparison of Relative Drag Coefficients for Phase III of Testing Conducted in the West Virginia University Closed Loop Wind Tunnel.

The parametric study on the upper surface (OVG3P) with 4 pairs of vortex generators started at the trailing edge with a small increase in drag and worked toward the leading edge. Parametric Position Number 3, which was approximately 10 inches from the leading edge recorded the greatest reduction in drag coefficient of these four tests. A similar parametric study was conducted on the lower fairing (OLFP) with 3 pairs of VGs was tested at three locations starting at the leading edge. These tests all show a reduction in relative drag coefficient, from moving the VGs upstream it was noticed that the position near the center of the lower fairing showed the largest drag reduction. It was expected that the VG size should be smaller than the boundary layer thickness, which is supported by the data where near the leading edge of the fairing where there is a smaller reduction in drag. The decrease in drag reduction further downstream can be explained by the increased thickness in the boundary layer making the VG less effective by reducing the ratio of VG height to boundary layer thickness. Therefore, it is best to place the VG where its height is approximately the boundary layer height, or slightly smaller than the boundary layer.

Figure 7 shows the dependence of the drag coefficient on the position of the vortex generator on the upper fairing. These tests were conducted with no vortex generators of the lower fairing. From this parametric study it was determined that, depending on where it is placed, the 1/8-inch vortex generator can either increase on decrease the drag on the model. The lower fairing was also parametrically studied as seen in Figure 8, where the center position resulted in the lowest drag reduction.

In an effort to investigate blockage effects, sheets of 1-inch thick foam were added to the walls to reduce the test section cross-sectional area. The standard deviations in the measured drag coefficients are listed in Table 7, along with the average change in drag for the tests conducted. Figure 9 shows the measured difference in drag coefficient for the two test section areas. Table 8 lists the change in drag coefficient and the test section areas for the two sets of tests. From this testing it was determined that test section blockage has a considerable effect on the effectiveness of the vortex generators.

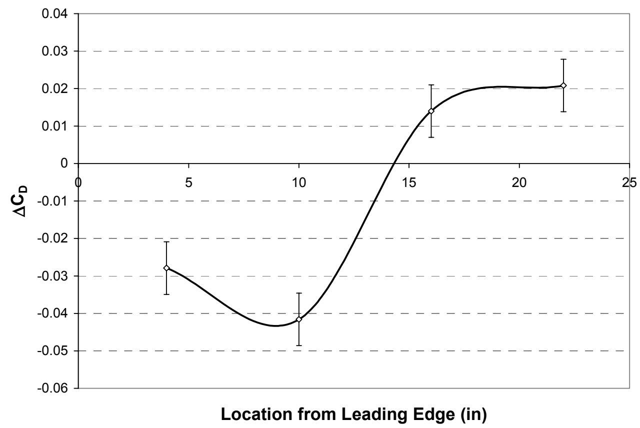


Figure 10: Upper Fairing Parametric Plot of Drag Coefficient as Dependent of Vortex Generator Location from the Leading Edge.

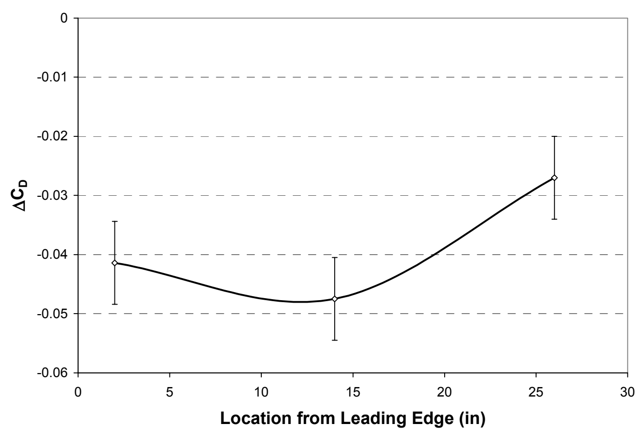


Figure 11: Lower Fairing Parametric Plot of Drag Coefficient as Dependent of Vortex Generator Location from the Leading Edge.

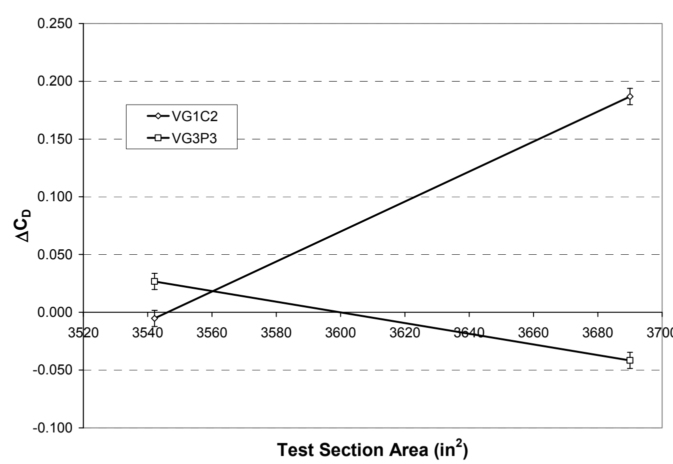


Figure 12: Effects of Test Section Blockage on the Drag Coefficient.

Table 7: Measured Change in Drag Coefficient and the Corresponding Standard Deviation for the Given Number of Tests Conducted During Phase III.

Test	Num. Of Tests	ΔC_D	StDev.
OVG1C1	4	0.2174	0.5619
OVG1C2	4	0.1868	5.4781
OVG2C3	4	0.1538	0.7966
OVG2C4	12	0.0594	9.6798
OVG3C4	12	0.0679	3.3087
OVG3C5	12	0.0441	5.6387
OVG3M1	12	0.04	7.0014
OVG3P1	12	0.0208	3.6601
OVG3P2	12	0.014	6.4425
OVG3P3	12	-0.0416	10.550
OVG3P4	12	-0.0279	9.0380
OLFP1	4	-0.027	0.5749
OLFP2	4	-0.0475	0.7691
OLFP3	4	-0.0414	0.3825
TSARVG1C2	4	-0.0053	0.0158
TSARVG3P3	4	0.02675	0.0034

Table 8: Effect of Blockage on Drag Coefficient and the Associated Test Section Area.

Test	T.S.Area (in2)	ΔC_D
VG1C2	3689.969	0.187
	3542.125	-0.005
VG3P3	3689.969	-0.042
	3542.125	0.027

In the blocked flow case the airflow is accelerated. This acceleration tends to reduce the size of the boundary layer. This would affect the desired size of vortex generator to be used. The best results in the Closed Loop Tunnel were with sub-boundary layer vortex generators. Therefore, the authors believe the optimal height of VG would be slight less than the boundary layer height in a given application.

CONCLUSIONS

In looking at the results for the 1/2-inch vortex generators it is evident that the height is too large for this application since all of the configurations tested increased the drag coefficient. As shown from the standard deviations of the data collected there is some randomness in the signal in the WVU testing that is partially caused by the turbulence in the wind tunnel created by the turn upstream of the test section and the model itself.

Phase I testing for the 1/4-inch vortex generator resulted in several configurations that showed relative reductions in the drag coefficient. Configurations 3 showed the largest drag reduction, with ΔC_D = 0.039. Phase II results for the 1/4-inch do not show any change in the drag coefficient; all the increases/reductions fall within the instrumentation error and therefore are essentially insignificant. The drag reduction measured during Phase I was a drag increase in Phase III. Again, the changes to the model were the only difference between the two sets of tests.

For the 1/8-inch vortex generator, Phase I testing resulted in all five configurations showing a drag reduction of 30 drag counts or more. However, when Configurations 4 and 5 were tested during Phase II the results were undetectable because they were within the error of the instrumentation. Configuration 5 was also tested in Phase III where a drag increase was determined.

In the WVU CLT tests a relative drag reduction was measured for all of the upper fairing parametric configurations. Despite the differences in the results from one phase to another it is important to note that configurations were found that produced a relative drag reduction. Phase II tests in the LFST were unable to show a reduction for the configurations tested. It is believed that with more testing time in the unblocked scenario configurations could be found to reduce the drag. This configuration would most likely contain smaller vortex generators closer to the leading edge of the model than the configurations tested.

The results from the WVU CLT tests may also simulate the aerodynamics of the motorcycle while riding in close proximity to another motorcycle. Thus the measured reduction in drag could be beneficial in passing other motorcycles.

In summary, the testing at WVU showed a drag reduction for several VG configurations. However, the testing at the LFST could not verify this reduction in an unblocked flow. Thus the configurations that worked in the WVU tests are not expected to work in a real world scenario, but they do show that it is possible to find some configurations that can reduce the drag. Further testing of different configurations and sizes of vortex generators would produce a reduction of drag in an unblocked wind tunnel and that would directly relate to a real world drag reduction. Therefore, the results from this research could assist in riding close to another motorcycle with negligible effects on drag in free air.

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ACRONYMS

CLT Closed Loop Tunnel

LFST Langley Full Scale Tunnel

ODU Old Dominion University

VG Vortex Generator

WVU West Virginia University

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