LAND YACHT AERODYNAMIC PERFORMANCE

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TABLE OF CONTENTS

ABSTRACT

In the competitive world of Land Yacht Racing (Sand Sailing), the aerodynamic characteristics of the vehicle must be known. Changing the parameters of the vehicle and testing the changes in the wind tunnel will give us a better understanding of the most efficient vehicle. The study outlined in this report clarifies the role of these parameters and their aerodynamic results.

Testing and analysis of various design changes indicated that substantial aerodynamic gains could be achieved. By fairing the wheels to reduce their drag and sealing the gap between the hard sail and the body, velocity increases are predicted to be as much as 37% above the baseline vehicle by the velocity prediction program.

INTRODUCTION

Land Yacht racing is a very exciting sport to many. A group of enthusiasts have gotten together and designed their own land yacht. They call themselves Land Yacht Design Individual Association (LYDIA). Each member of LYDIA contributes their own ideas and experiences into the design of the land yacht.

The design that LYDIA has come up with is shown in Figure 1. It is composed of a hard sail rather than a soft sail as seen on most land yachts. The idea of the hard sail is a fairly new idea and is still being tested and refined. The land yacht also has a tail which moves according to the angle of the wind and in turn rotates the hard sail. This was designed to help control the hard sail during wind shifts, so all the pilot has to do is fine tune the hard sail.

To better understand land yachts, it helps to understand a little about land yacht racing. Unlike sail boats these sail crafts operate at about three to four times the wind speed, reaching velocities of seventy to eighty miles per hour. Even though these crafts don't have the history of many centuries old sailboats, they have come a long way since their they were introduced at the turn of the century. The current speed record for land yacht racing stands at 94.7 mph.

The land yacht races consist of several classes of vehicles based on their sail area. The races consist of a closed course circuit marked on a dry lake bed with a start/finish line. The speed of the vehicle and the ability of the pilot to control the land yacht are

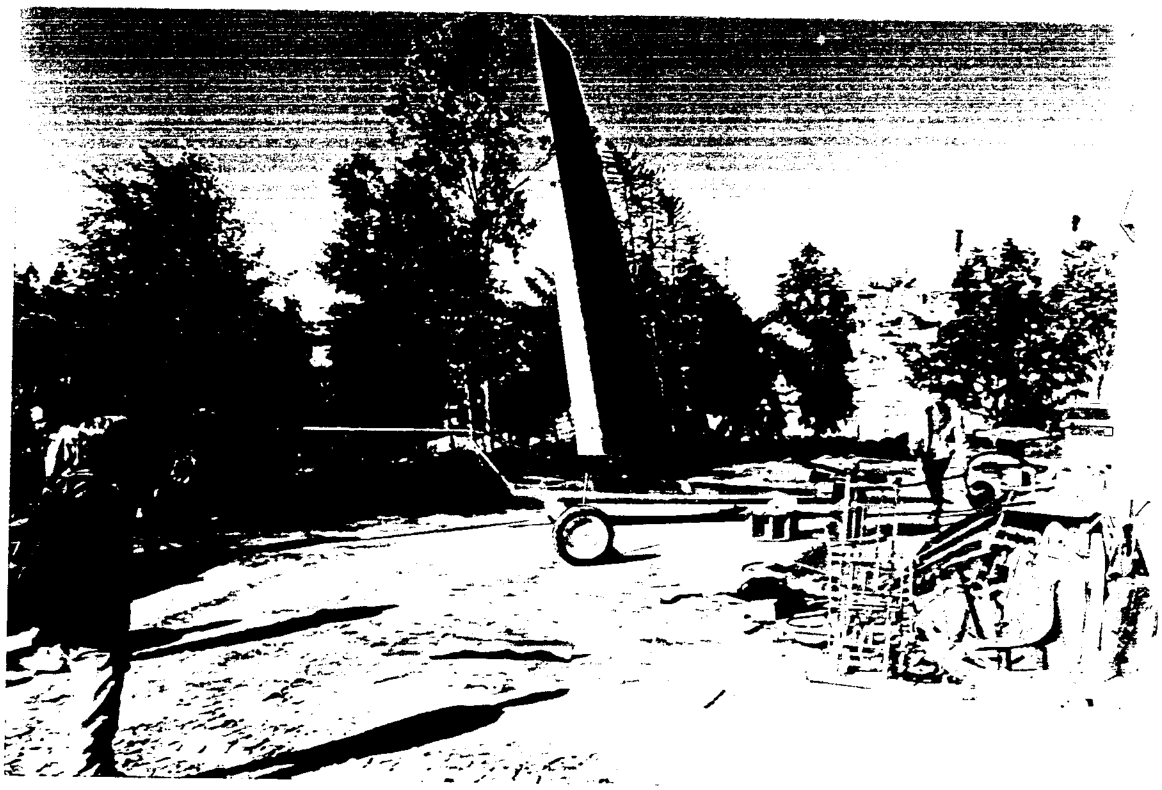


Figure 1 - Full Size Land Yacht designed by LYDIA

some of the important racing factors.

Since the vehicle's success is based on the performance and speed of the vehicle, LYDIA has asked us to test a model of their design in the wind tunnel. Our objective was to determine a more efficient vehicle design by testing and analyzing the following: body sweep, flap deflection, tail on/off, closing the gap between the hard sail and body, and wheel changes. The information obtained was used to predict velocity on the full size land yacht.

EXPERIMENTAL SET-UP AND PROCEDURE

In order to minimize wall effects inside the wind tunnel, we kept the model dimensions at a maximum of 80% of the wind tunnel width and height. Therefore we were able to construct a 1/8 scale of the original vehicle. To achieve this maximum model scale, the model was built on the basis that it would be mounted on its side, inside the wind tunnel test section. With the angle of attack of the hard sail at a maximum, we determined the maximum blockage for the model to be 5.2%. This is well below the 7% established blockage limit.

A NACA 0018 airfoil was used for the hard sail and flap. The hard sail of the model was milled from aluminum, linearly tapering and twisting. The hard sail was made with a 1.75 degree of twist to better model the wind gradient effect on the full size land yacht. The flap was not made as long as the sail on the assumption that at this length the sail and flap would stall uniformly. This was done on the model as well as the actual vehicle.

Six N-C machined wheels were manufactured for this model ranging from height, width, and fairing/no fairing. These were made and designed by LYDIA in order for us to test the aerodynamic forces on each wheel. From our results, LYDIA would be able to determine if they needed to redesign the wheels on the full size land yacht. Figure 2 shows the six different sets of rear wheels. Wheel #1 is a model of the wheels that are now on the original land yacht. The front wheel was also machined and modeled from the full size land yacht.

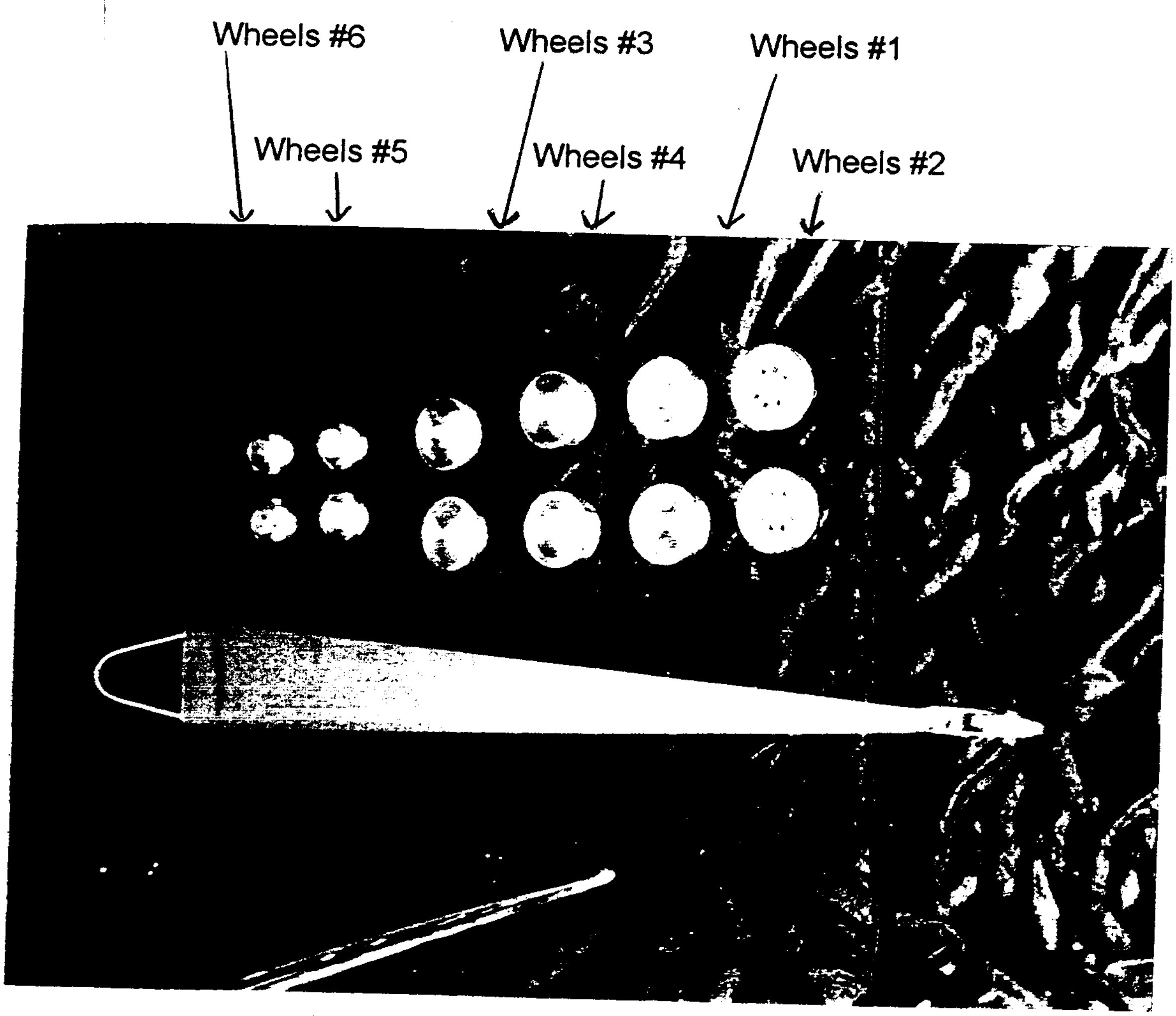


Figure 2 - Model Wheels and Body

Figure 2 also shows the model of the body. This was made from a piece of foam with fiberglass over it. The tail of the land yacht was an off the shelf, untapered wing section of equal scale area to the full size vehicle. A vertical ground plane spanned the height of the wind tunnel section where the vehicle wheels were located. The .2 inch gap between the ground plane and wheels were filled by pieces of foam to prevent vibration.

Once the model was built and assembled, it was placed in the wind tunnel on a three point mount force balance. Prefabricated bayonets were used in conjunction with extensions to center the model in the wind tunnel test section. To control the angle of attack of the hard sail, an extension was attached to a jack screw. The angle of the body with respect to the oncoming wind was varied independently from the hard sail. Drawings of the assembled vehicle with dimensions, forces and moment orientations, are shown in three different views in Figures 3a, 3b, and 3c. Figure 4 is the land yacht model as mounted in the wind tunnel.

Once the model was mounted, we were ready to begin our testing. All of the tests were done at a tunnel speed of 120 mph. From this, the Reynolds Number was calculated to be approximately 780,000 based on the root wing chord of 5 inches. This works out to a full size vehicle speed of 20 mph.

We did fourteen different sets of tests, doing an alpha sweep from -2° to 16° in increments of 2° for each test. A tare run without the model was performed and the

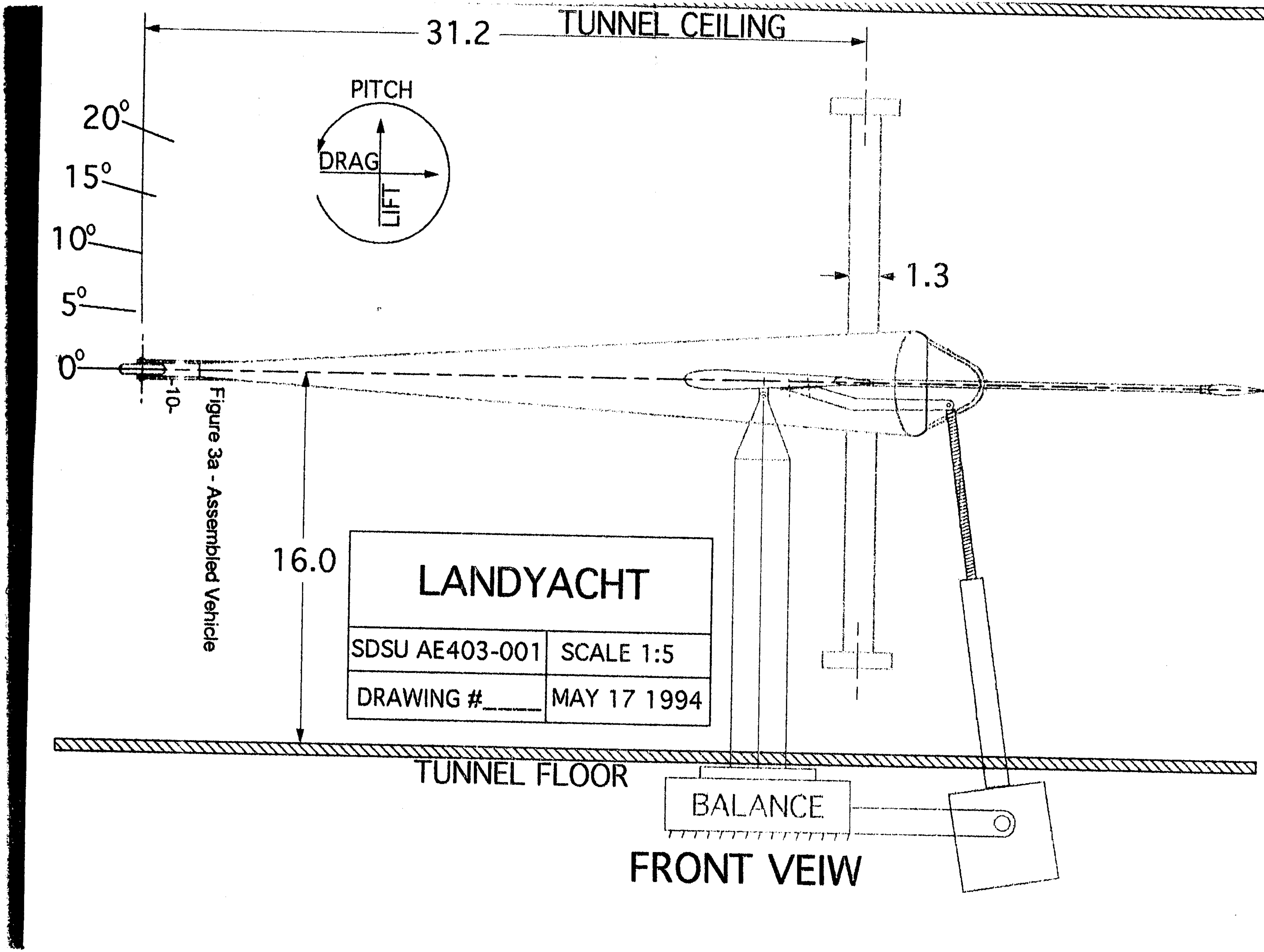


Figure 3a - Assembled Vehicle

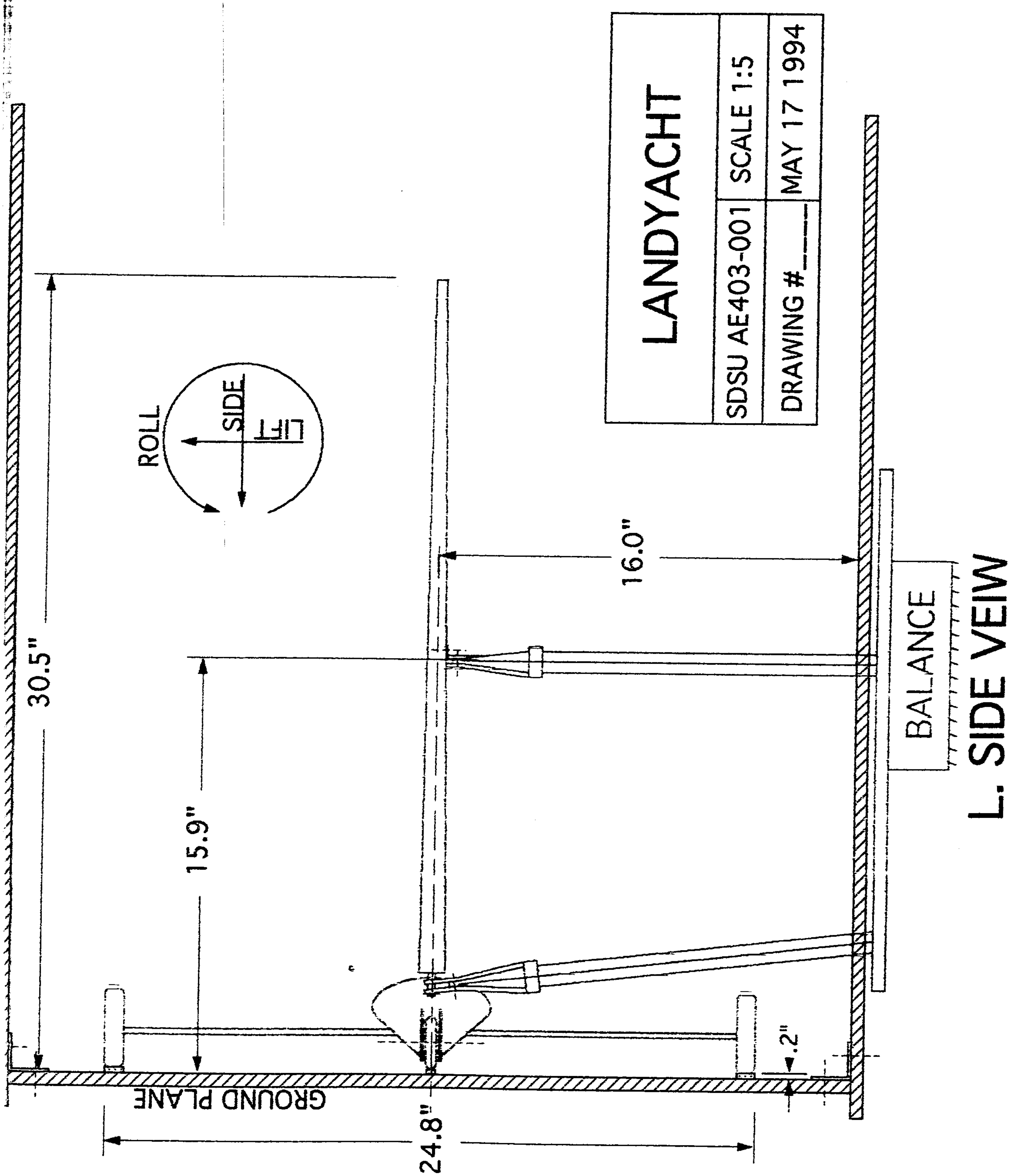


Figure 3b - Assembled Vehicle

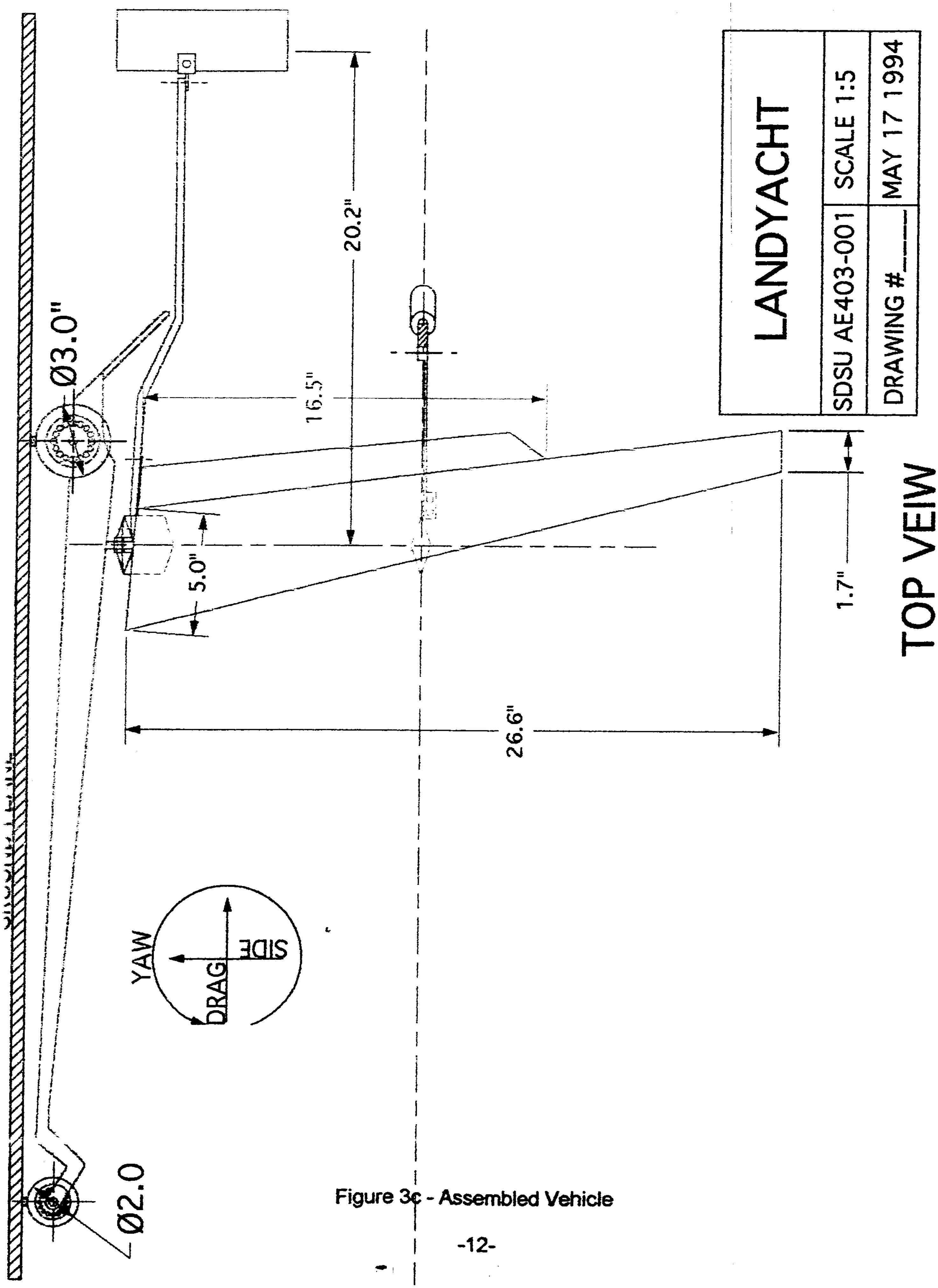


Figure 3c - Assembled Vehicle

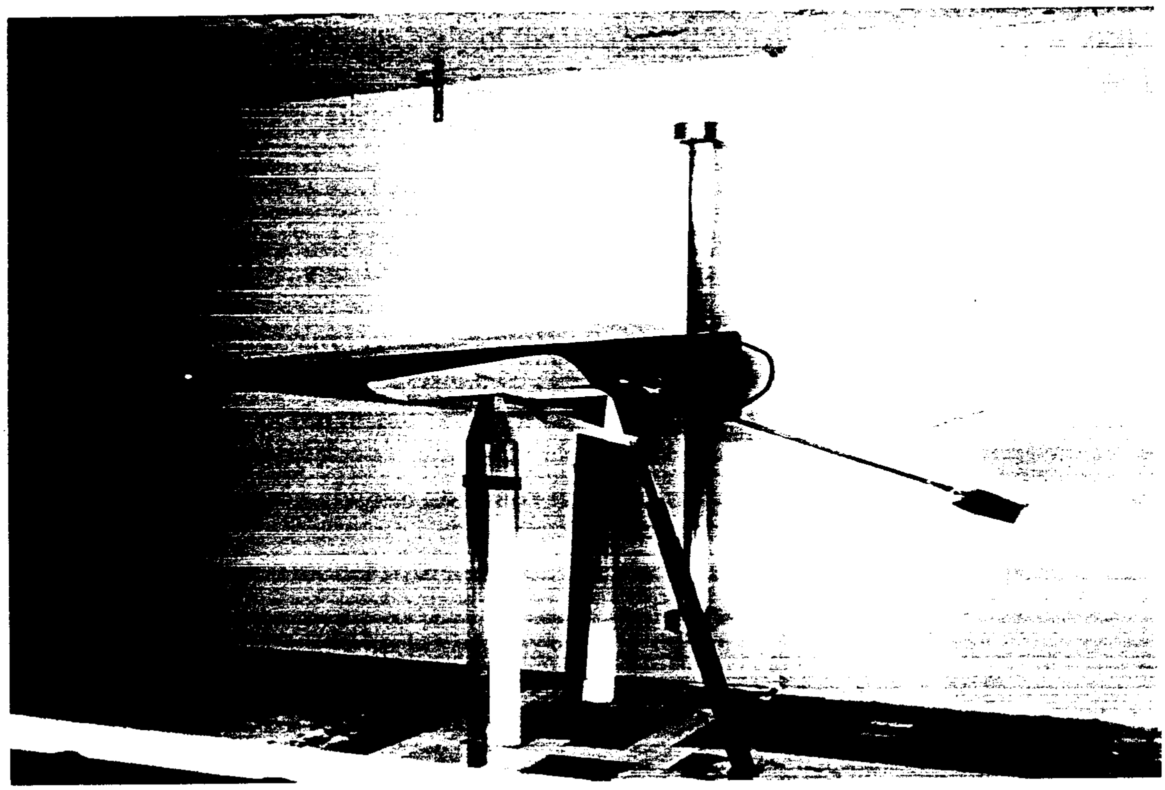
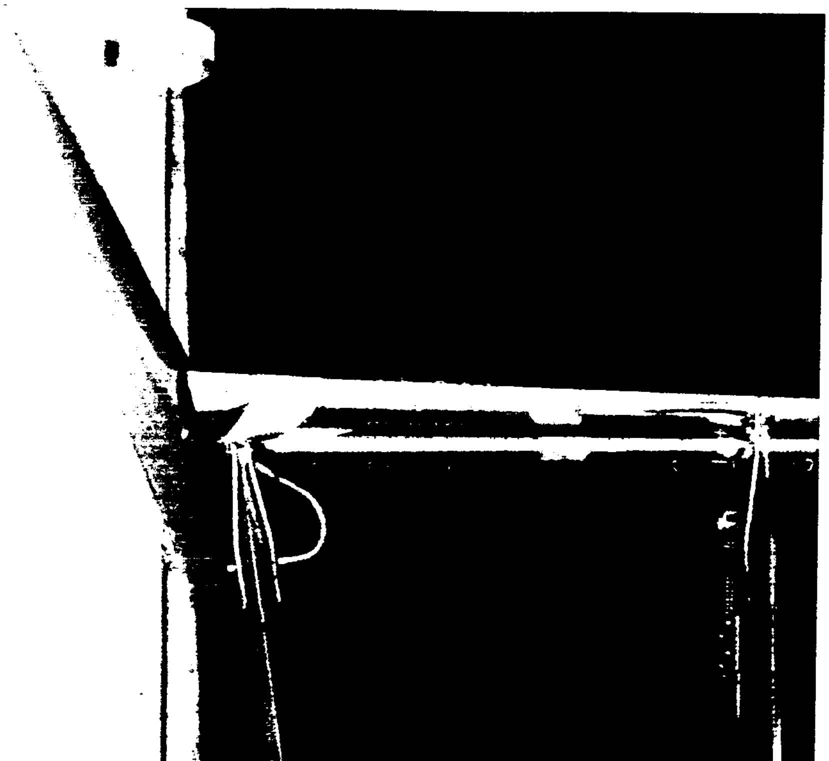


Figure 4 - Land Yacht Model Mounted in Wind Tunnel

results were subtracted from all other tests. By running the wind tunnel with tuffs on the flap and the hard sail, we were able to determine that the majority of the hard sail stalled at approximately 11°.

Our first set of tests was a body sweep. This test consisted of changing the body angle with respect to the air flow. Tests were done for a body angle of 0°, 10°, and 20°. During land yacht racing, the body of the land yacht with respect to the wind is usually between 15° and 25°. Therefore, for the remainder of the tests, we kept the body of the land yacht at 20°. The next set of tests was changing the flap deflection. We tested flap angles of 0°, 5°, 10°, and 15°. With the body at 20° and the flap at 10°, a test was run with the tail off. Because of the vibration of the tail in the wind tunnel, we kept the tail off for the remainder of the tests. Further tests consisted of closing the gap between the hard sail and the body. Figure 5a shows a thin sheet of aluminum used to close the gap. Figure 5b shows the model with the gap. We also did a set of tests with no wheels and different wheels. These wheels were previously shown in Figure 2 on Page 8. Once we finished with that, we took the body of the land yacht out of the wind tunnel and did an alpha sweep of just the hard sail alone. From these tests, we were able to determine a more efficient land yacht design and use this in a velocity prediction program. However, in order to understand the results and conclusions we need to explain the velocity prediction program.

Figure 5a - Closed Gap Between Hard Sail and Body



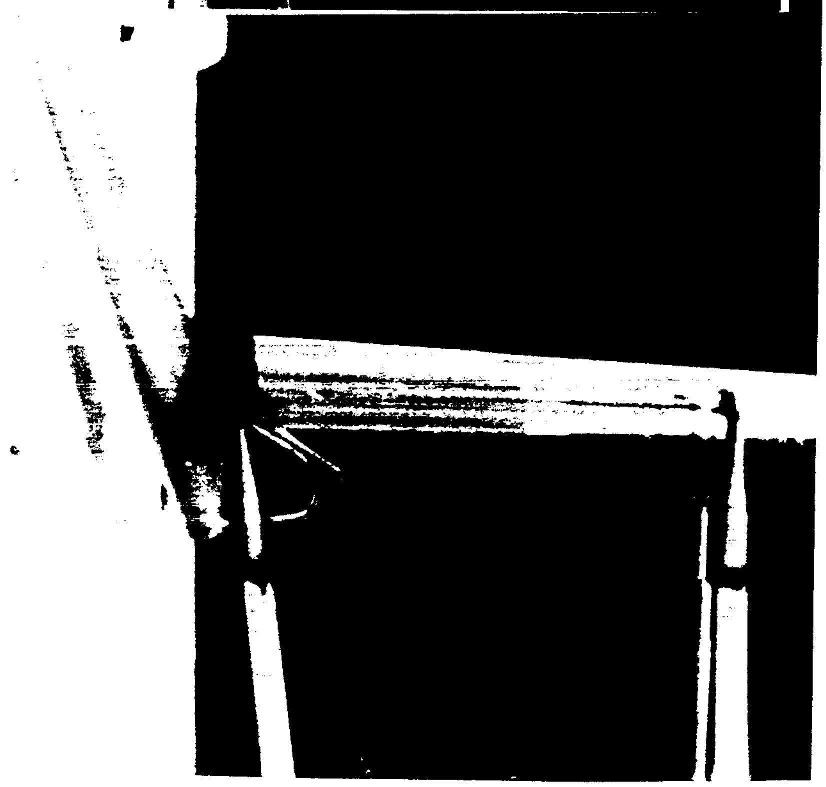


Figure 5b - With Gap Between Hard Sail and Body

VELOCITY PREDICTION PROGRAM

A Velocity Prediction Program (VPP) is a computer software tool used in predicting the performance characteristics of a vehicle. By use of static and dynamic characteristics of a yacht, derived from theory and the wind tunnel, it is possible to predict the velocities achieved by a land yacht for a given course angle and wind speed. The program can also be calibrated by full size yacht tests to more accurately predict future design changes.

These changes could be small changes on an existing vehicle or the design of a new yacht. This allows for a faster and more efficient design process, saving both time and money. Since this yacht is sailed around a closed course, the polar velocity diagrams generated by the VPP can be analyzed to find the most efficient course to sail for a given wind velocity.

Finally, knowing the performance envelope in which the boat will operate in helps the engineers design the structures of the vehicle to withstand the forces it will experience. Besides the obvious safety this gives, it can save costly weight.

To understand how the VPP calculates speed, one must understand what makes a Land Yacht go. The wind velocity triangle shown in Figure 6 consists of the true wind, the wind caused by the boat's speed, and the vector sum of the two, or apparent wind. From this it is obvious that the wind velocity the hard sail operates in is greater than the true wind speed. The hard sail of the yacht generates lift and drag from the apparent

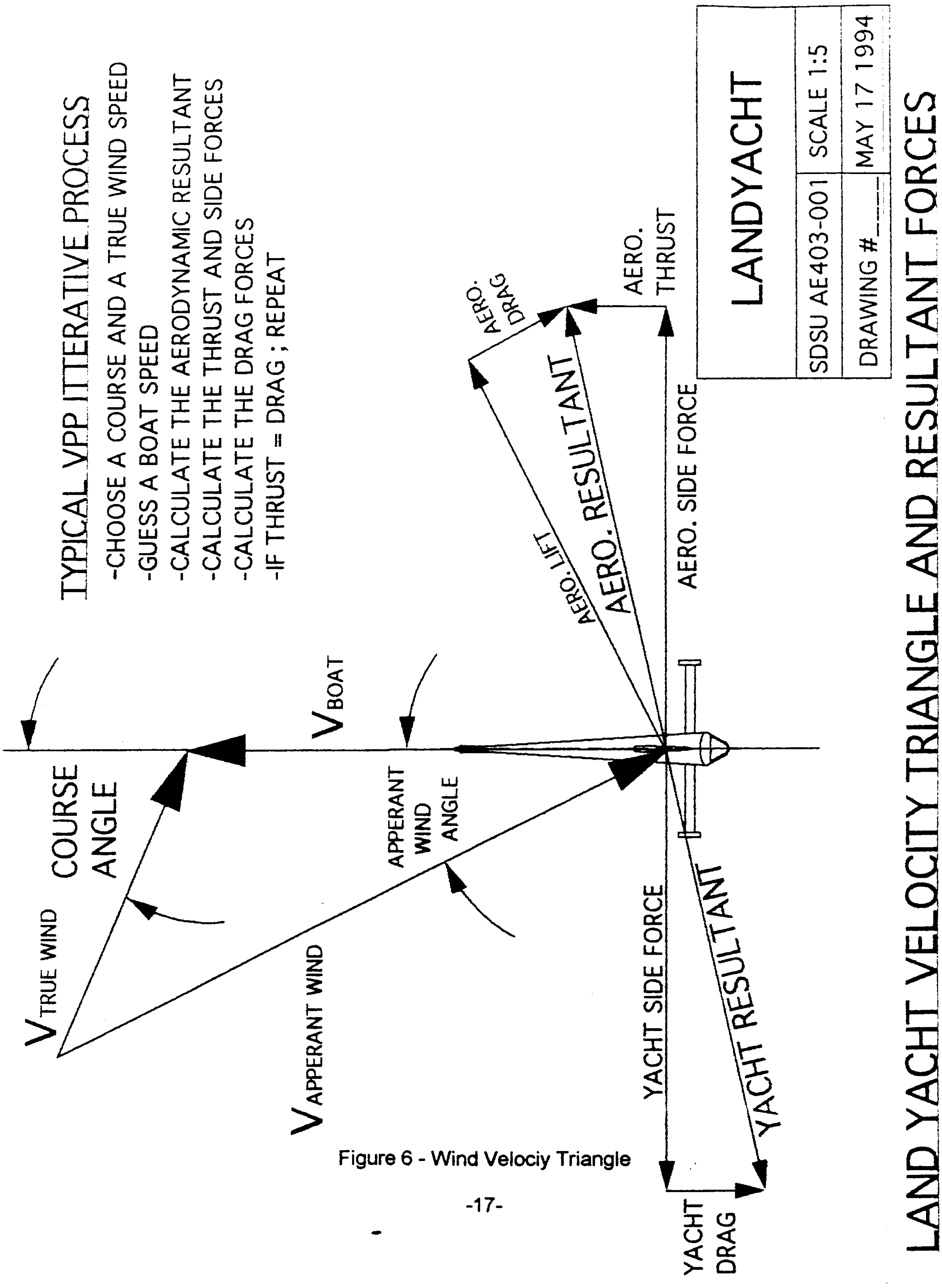


Figure 6 - Wind Velociy Triangle

wind, much like an airplane. The component of the resulting aerodynamic force in the direction of travel of the yacht is the thrust. This can be measured in the wind tunnel for various speeds and angles.

Unfortunately, this resultant force also has a large component perpendicular to the direction of travel. This side force must be resisted by the land yacht's wheels. When the wheels generate this equal and opposite side force, a drag force is also produced. This drag can be calculated or measured for the purpose of the velocity prediction.

When the thrust equals the drag, the vehicle is in equilibrium and the maximum steady state speed has been reached. There are limits to the magnitude of the resultant forces. Too much force can cause the boat to tip over or slide out, and the wing can only generate so much lift.

These forces and velocities can be solved for by simultaneous equations or an iterative process involving guessing a boat speed until thrust is equal to drag.

RESULTS

During our testing, we were primarily concerned with the Lift Force and Drag Force. By using equations (1) and (2) we were able to determine C_D and C_L.

$$C_D = \frac{D}{q \cdot S} \tag{1}$$

$$C_L = \frac{L}{q \cdot S} \tag{2}$$

In these equations, q is the dynamic pressure and S is the planform area of the hard sail. L and D are the Lift and Drag forces, respectively. These are measured by the balance in Pounds. With these equations, we were able to plot C_D and C_L for our tests and form conclusions.

The first thing that we analyzed was the flap deflection. Figure 7 shows a plot of C_L/C_D vs. C_L for each flap deflection, from 0° to 15°. These results show that the best lift to drag ratio is achieved at a flap deflection of 10°.

Next we studied the tail on and tail off configuration. From these two tests, we were able to plot C_D vs. C_L for no tail and the tail equal to alpha. By adding the tail drag at 0° alpha to the tail off drag we plotted a tail equal to 0° sweep. Figure 8 shows these three plots. From this graph, it is clear that when the tail is kept at 0° with respect to the airflow, the land yacht produces more drag. The most efficient tail configuration is when the tail is equal to alpha because the lift from the tail adds to the lift of the hard sail.

Flap Deflection

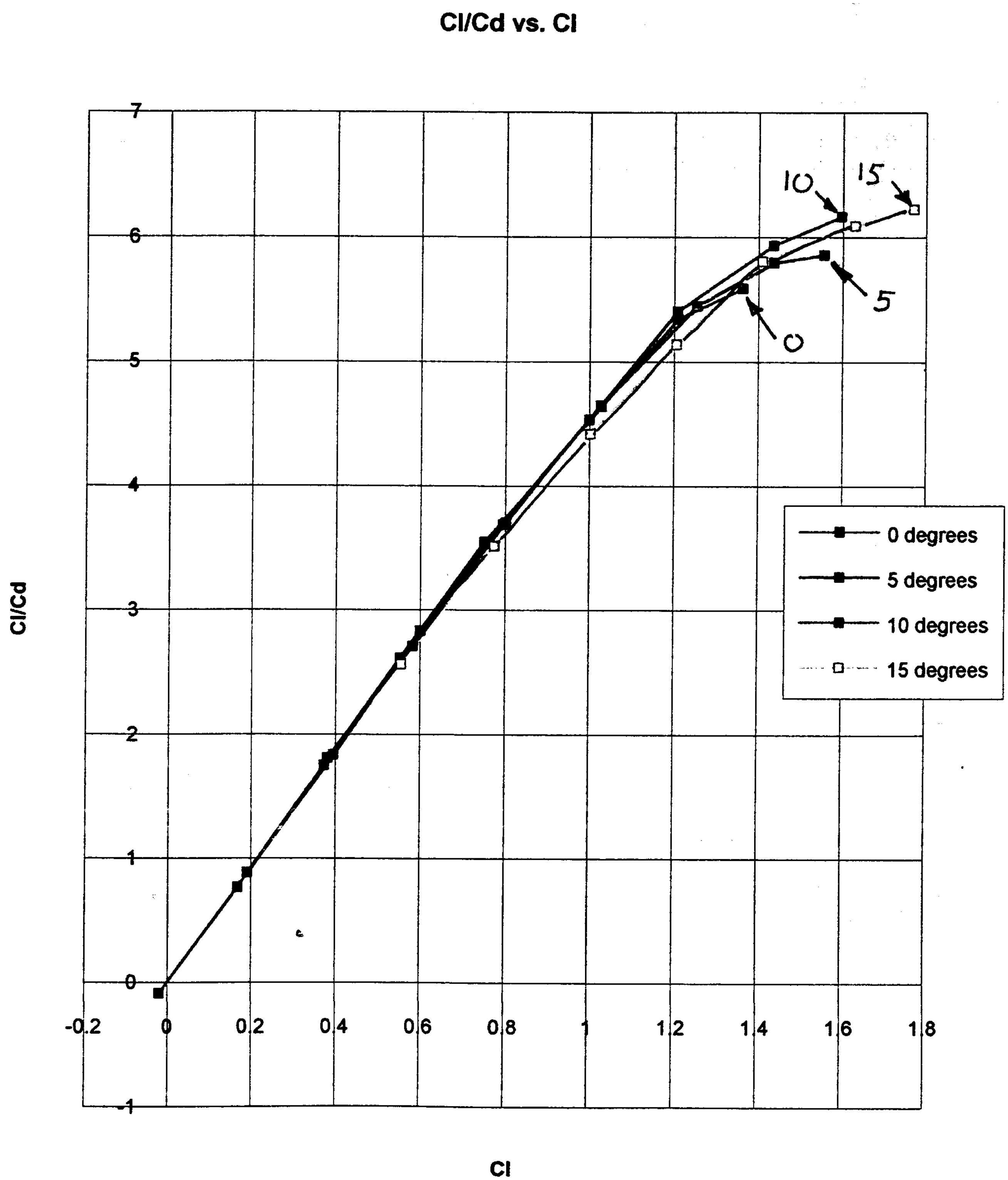


Figure 7

Tail

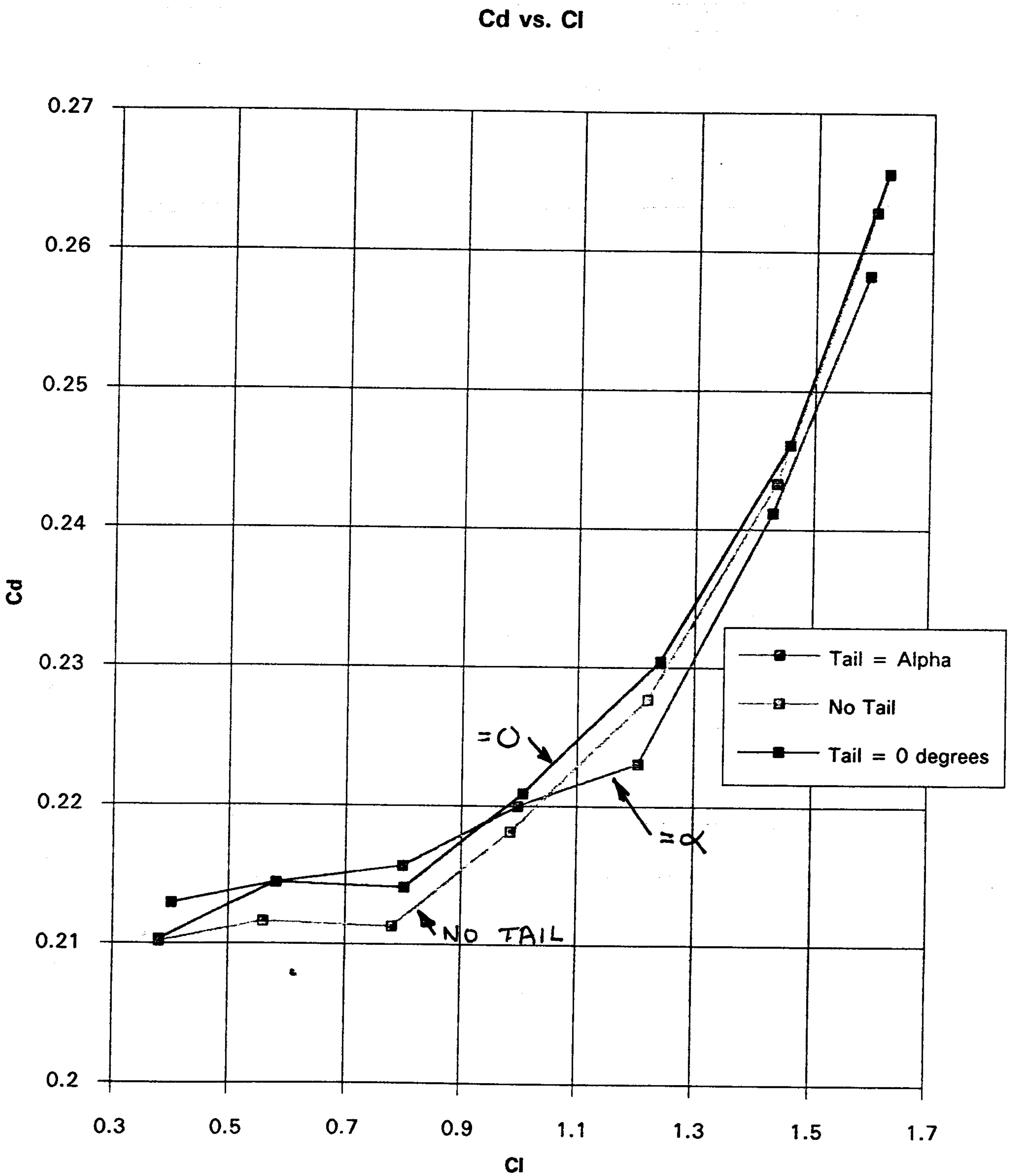


Figure 8

Next we took a look at the data obtained from closing the gap between the hard sail and the body of the land yacht. Figure 9 shows that by closing this gap we have achieved a significant decrease in drag and more lift, increasing the efficiency of the land yacht.

The results we found from the various wheel changes were extraordinary. It is obvious from Figure 10 how much drag is produced by the wheels. The wheels that are on the full size land yacht are Wheels #1. The graph shows a large decrease in drag of the land yacht when we took these wheels off. By referring back to Figure 2 on Page 8, we can see that Wheel #3 is the same as Wheel #2, but it has a fairing. The fairing on Wheel #3 decreases the drag also. Wheel #6 is smaller in diameter than Wheels #1 through #4. This also decreases the drag, but adds to the rolling resistance of the vehicle. Wheel #4 was not tested because of time constraints on wind tunnel testing. Wheel #4 is the same as Wheel #1, but with a fairing, therefore, the results will be similar to those of Wheel #2 and Wheel #3.

From the tests without the tail, the test without the wheels, and the test with the hard sail alone, we were able to approximate the amount of drag caused by various parts of the land yacht. For a body angle of 20° and a flap deflection of 10°, we were able to come up with the pie charts of drag contributions shown in Figures 11a and 11b. These charts clearly show how much drag is produced by just the wheels.

GAP CHANGE

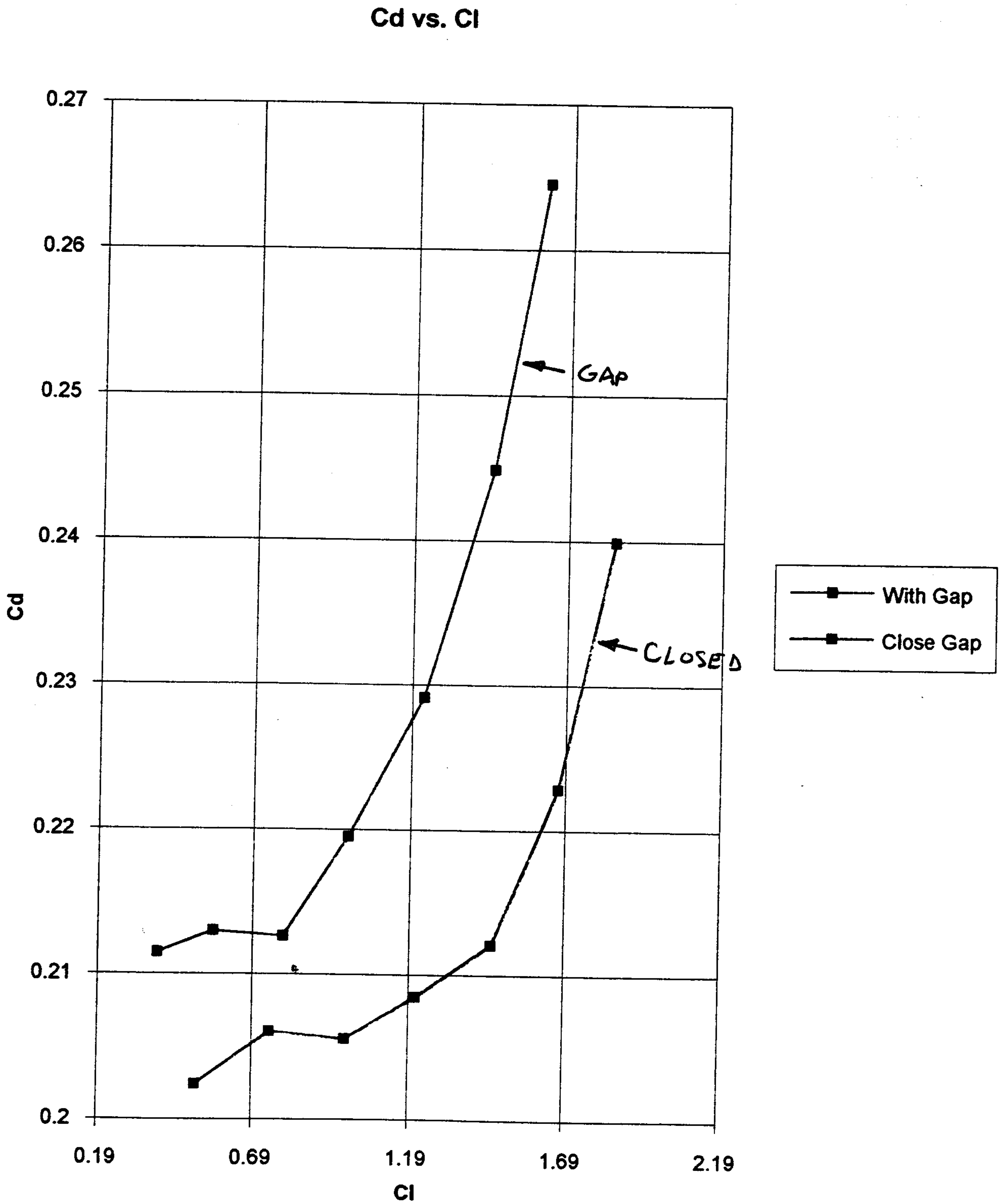
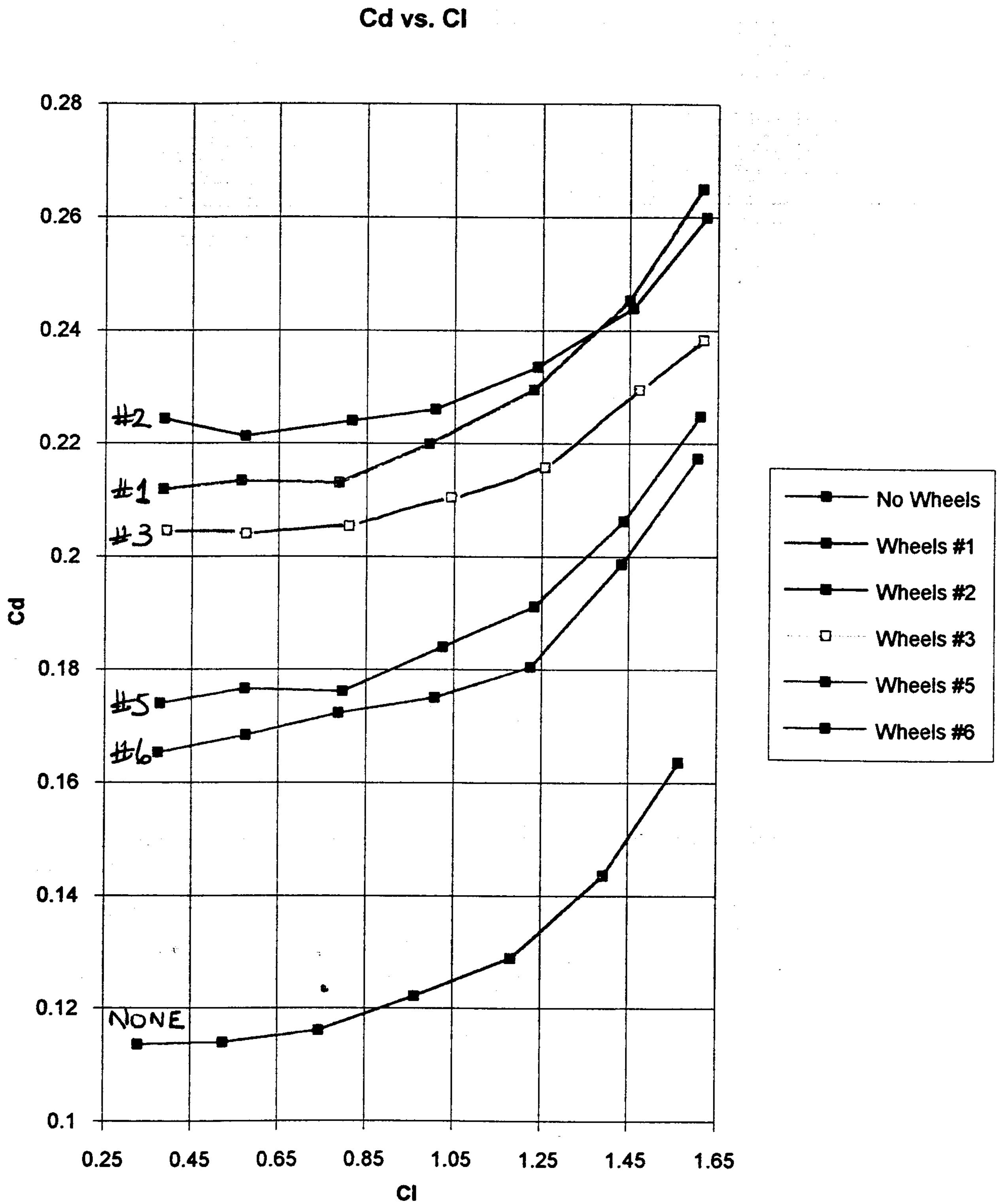


Figure 9



Cd vs. Cl
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
Cd
0.25
0.45
0.65
0.85
1.05
1.25
1.45
1.65
Cl
#2
#1
#3
#5
#6
NONE
No Wheels
Wheels #1
Wheels #2
Wheels #3
Wheels #5
Wheels #6

Figure 10

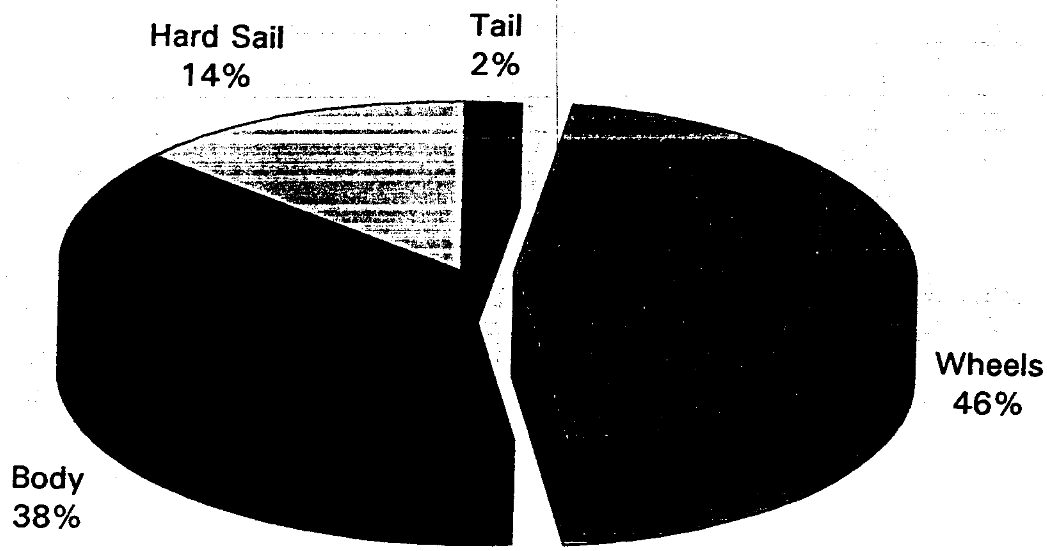


Figure 11a - Drag Components for Alpha = 0 degrees

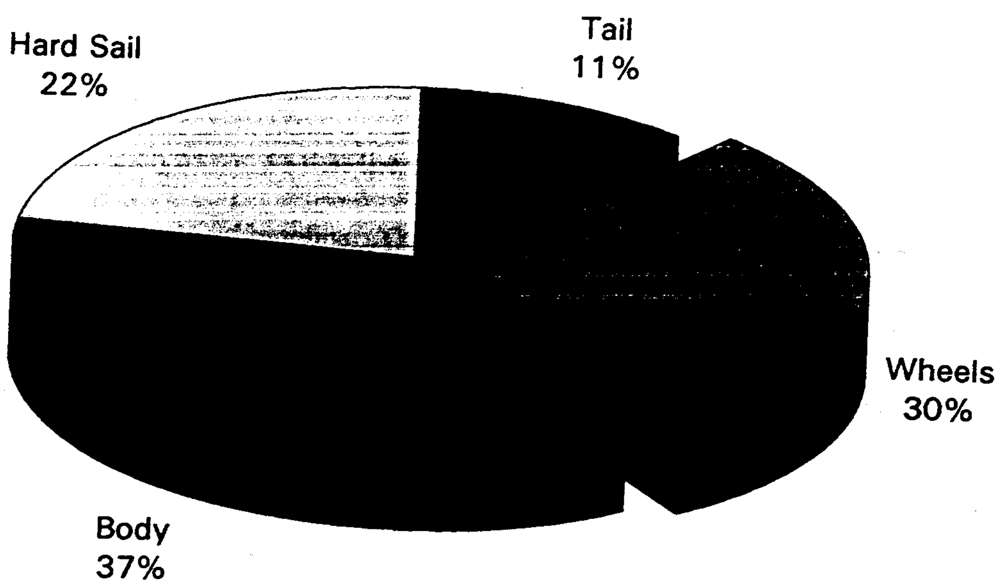


Figure 11b - Drag Components for Alpha = 10 degrees

Now that the aerodynamic characteristics of the yacht are known, they can be input into the Velocity Prediction Program. This is done by curve fitting the wind tunnel drag vs. lift data with the parabolic drag equation:

$$C_D = C_{D0} + C_L^2 K_i \qquad (3)$$

The curve fitting of the baseline vehicle is shown in Figure 12 and the curve fitting of our "Best" Vehicle is shown in Figure 13.

With this accomplished, the VPP outputs velocity curves on a polar coordinate system with the radius (R) and the coordinate (θ) representing the yacht velocity and course relative to the true wind direction respectively. Figure 14 shows velocity polars for both the theoretically derived baseline yacht, given to us by LYDIA, and the San Diego State wind tunnel tested baseline. These are overlaid for comparison purposes at various true wind speeds.

This analysis shows that the wind tunnel predicted velocities are as low as 72% of the supplied theoretical baseline. The Velocity Made Good (VMG) can also be read from the polar diagram. This is the component of the yachts velocity into the true wind and is a function of both the land yacht's speed and direction. It is an important aspect of performance for a vehicle which races around a course.

Curve Fitting of Baseline Wind Tunnel Drag

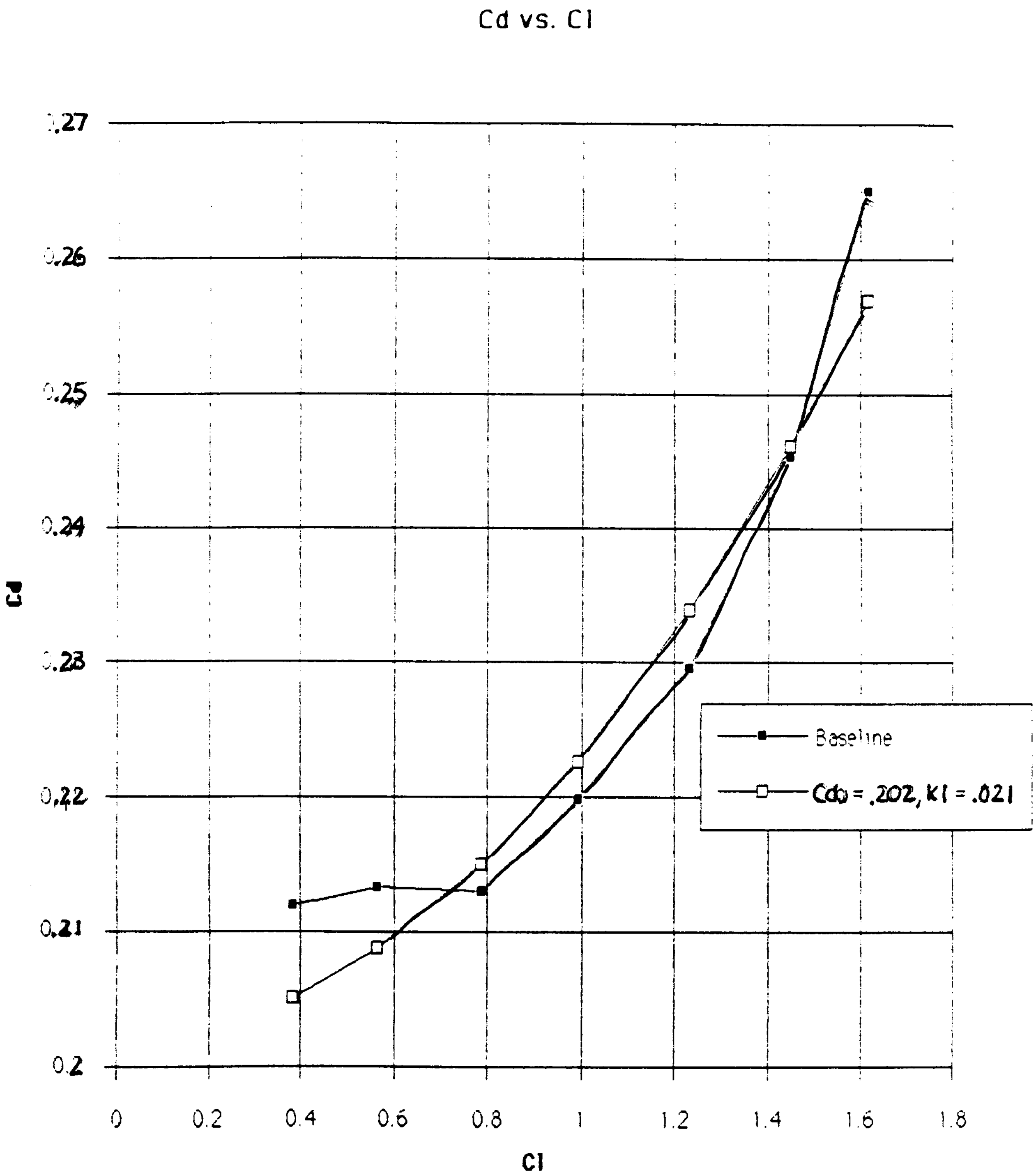


Figure 12

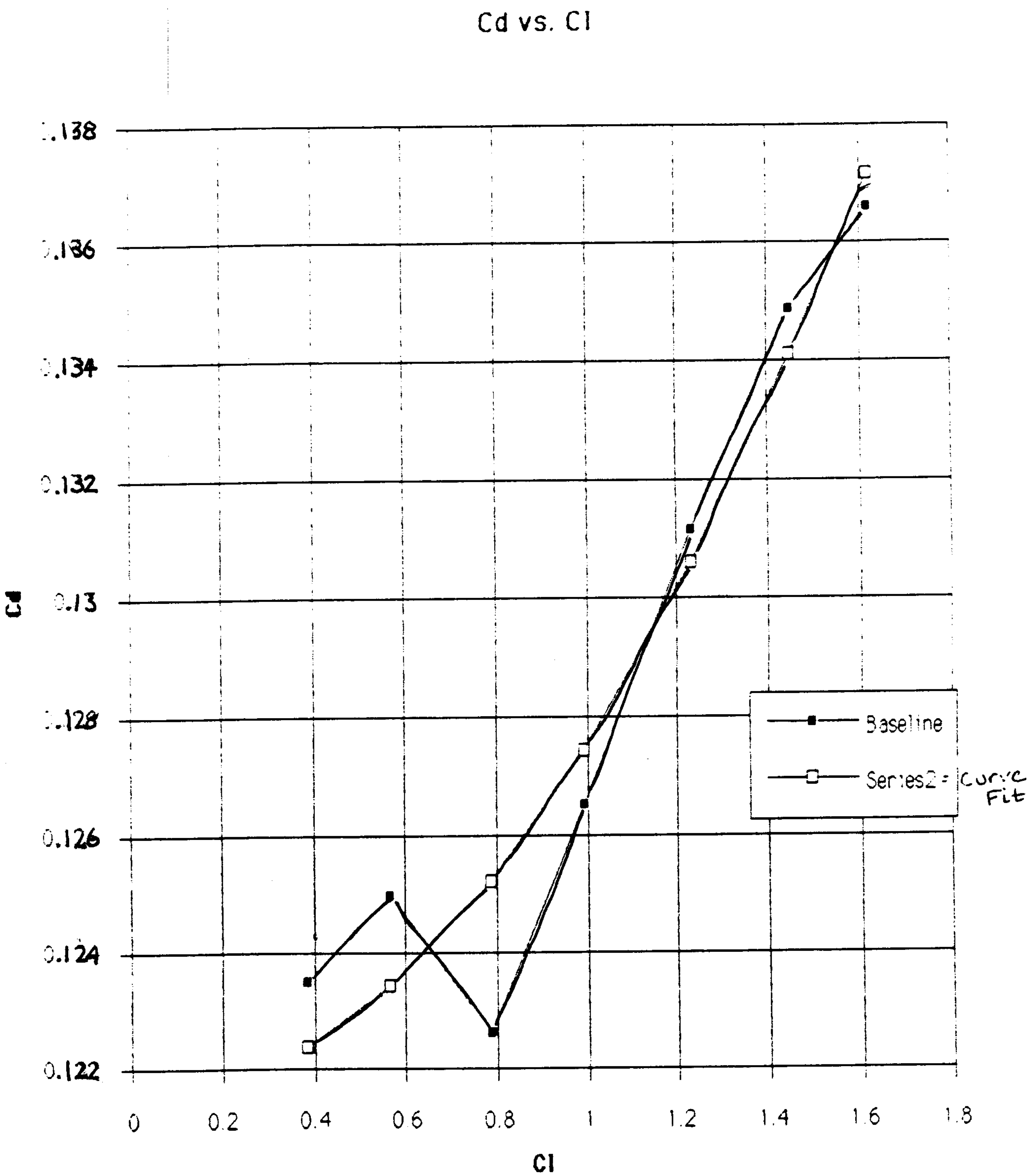
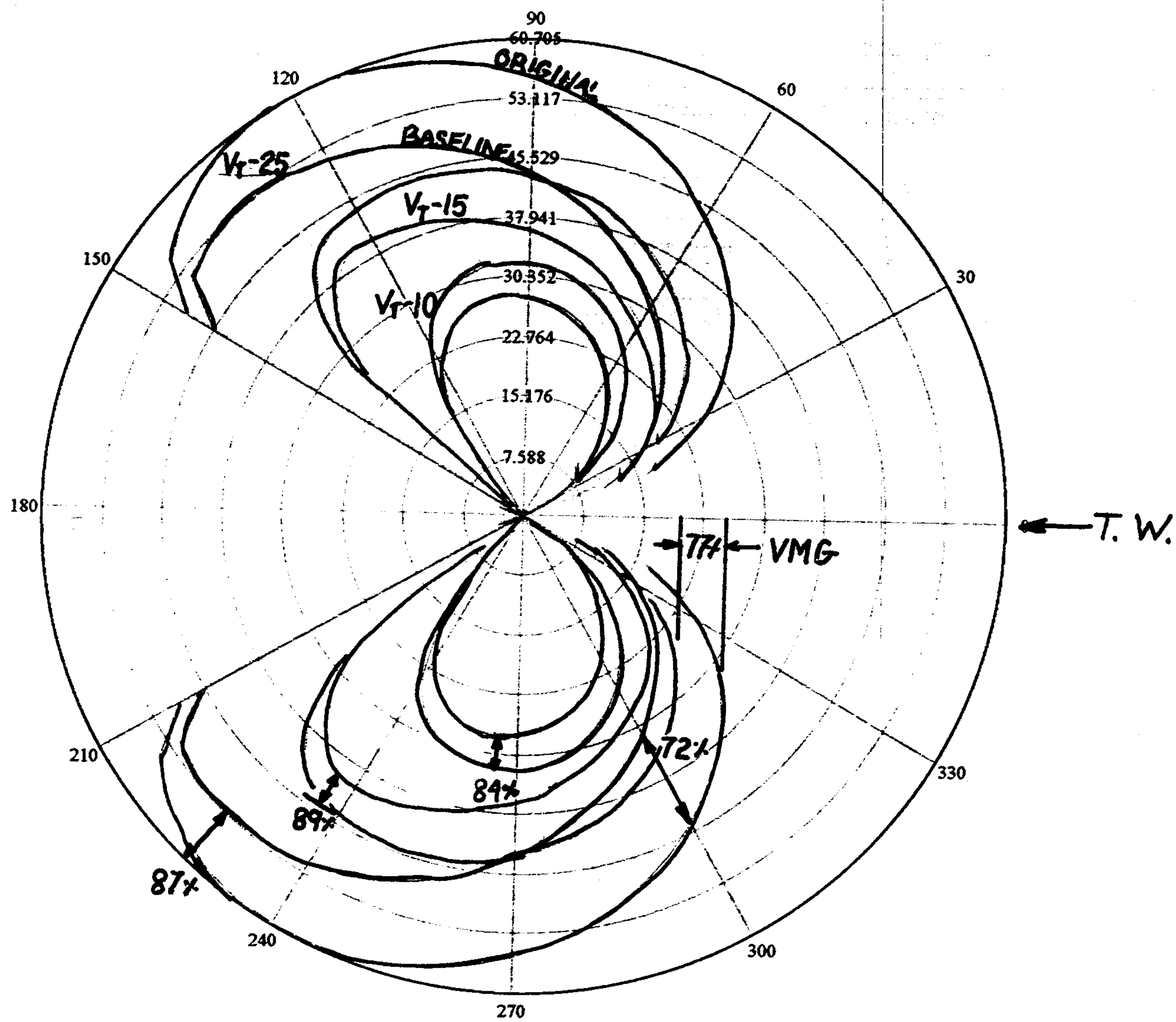

Cd vs. Cl
0.138
0.136
0.134
0.132
0.13
0.128
0.126
0.124
0.122
Cd
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Cl
Baseline
Series2 = Curve Fit

Figure 13

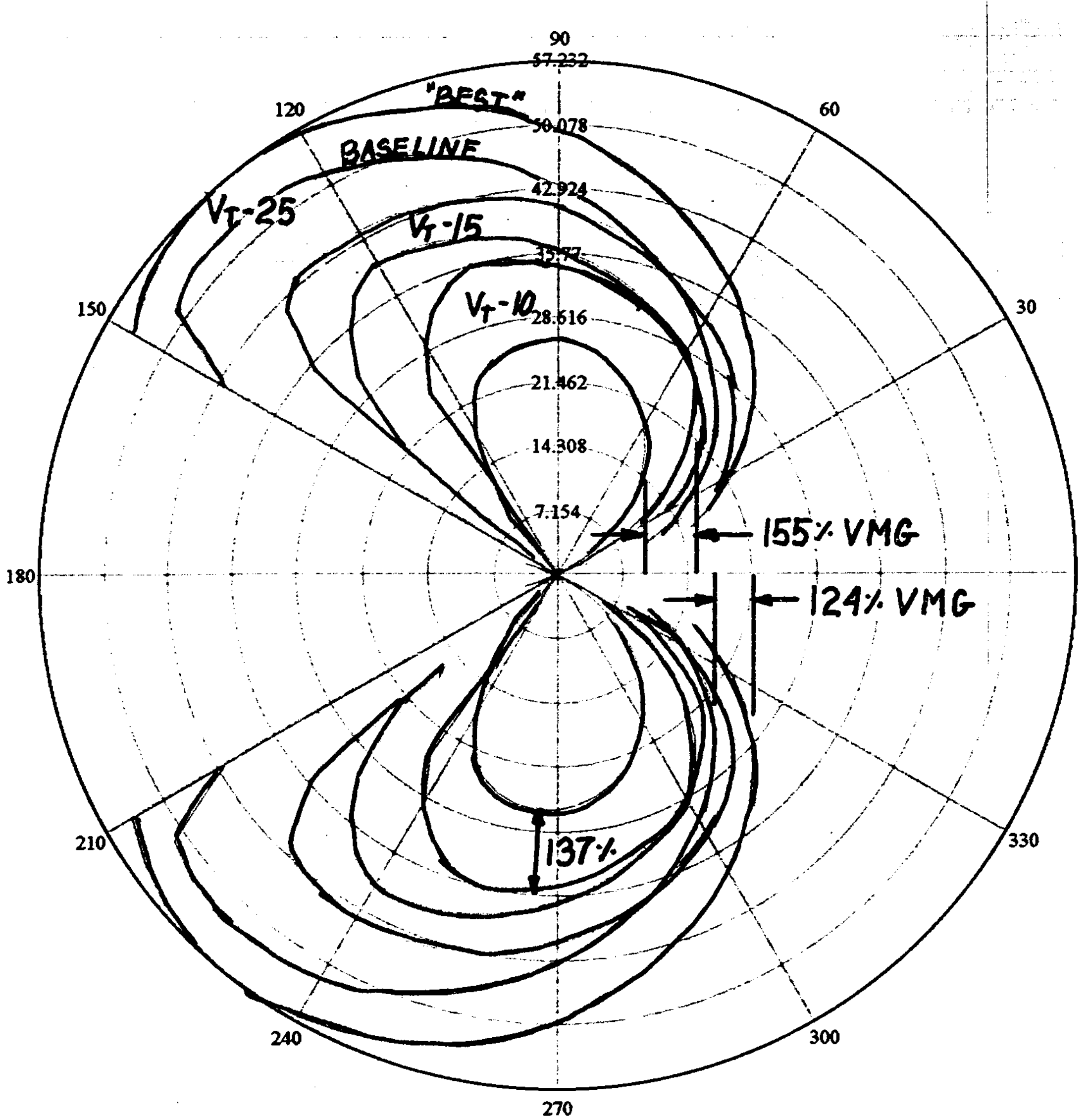


VELOCITY POLAR

Original Estimate & Wind Tunnel Baseline

Figure 14

Next, we compared the baseline with what we determined was the "Best" wind tunnel tested land yacht (Figure 15). This "Best" land yacht implements the closed or sealed wing gap and a reduction of aerodynamic wheel drag of 80%, which is assumed to be achievable with fairings. Overall velocity gains of up to 37% over the baseline are predicted for the "Best" land yacht, representing increases of over 9 mph for the lower wind speeds. VMG deltas of over 50% may be achieved and represent a lead, in a race, of one minute for a three minute upwind leg of a course. This is obviously a dramatic performance difference.



VELOCITY POLAR

Wind Tunnel "Best" & Wind Tunnel Baceline

Figure 15

CONCLUSIONS

The wind tunnel measured aerodynamic characteristics that are very different and assumably more accurate than theoretical estimates. This is very helpful in determining a land yacht's expected performance. Design changes can be accomplished quickly, easily, and tested definitively in the wind tunnel.

This process of land yacht performance testing removes one of the most unreliable variables of land yacht racing, the pilot. Since a large number of trim setups can be tested, one is not constrained by the human factor of judgment, but has hard facts to guide the way.

Toward the ultimate goal to make land yachts faster, wind tunnel results, in combination with analytical tools, such as the velocity prediction program, can be utilized to achieve results more quickly and safely than the current trial and error methods used today.

DESIGN RECOMMENDATIONS

If further wind tunnel testing was done with this land yacht, we would recommend that faired wheels be tested in order to better determine the decrease in drag that this would produce. Also, more body sweep angles could be tested to get a more accurate determination of the Lift and Drag at different apparent wind angles. The speed of the wind tunnel could be changed to predict land yacht performance at various speeds.

Our design recommendations for the real vehicle include fairing the wheels and closing the gap between the hard sail and body. Due to pilot visibility, this would have to be done so that the pilot would be able to see through it. We also recommend putting instruments on the full size land yacht to measure its velocity. This will help to compare the results found in the wind tunnel with the actual performance of the land yacht.

REFERENCES

Embroden, Nord, Landyachts: Practice, Theory, and Design, 1972.

Marchaj, C.A., Aero-Hydrodynamics of Sailing, Dodd, Mead & Company, New York, 1989.

Parr, Andrew, Sandyachting, Gomer Press, 1991.

Rae, William H., and Alan Pope, Low-Speed Wind Tunnel Testing, John Wiley & Sons, New York, 1984.

Ross, James C., Aerodynamic Design of a Rigid-Wing Sail for a C-Class Catamaran, Sailtech Conference, 1989.

Appendix A

Computerized Calculations

Alpha	Body - 0 degrees				Body - 10 degrees				Body - 20 degrees			
	Lift (LB)	Drag (LB)	Cl	Cd	Lift (LB)	Drag (LB)	Cl	Cd	Lift (LB)	Drag (LB)	Cl	Cd
-2	-2.61812	3.586264	-0.12073	0.165374	-1.54208	4.563875	-0.07111	0.210454	-0.41365	4.779247	-0.01907	0.220386
0	1.143696	3.444759	0.052739	0.158848	2.803452	4.546659	0.129276	0.20966	3.633096	4.735192	0.167533	0.218354
2	5.581301	3.338818	0.257371	0.153963	7.36156	4.432417	0.339464	0.204392	8.077044	4.611704	0.372457	0.21266
4	10.06025	3.329478	0.463909	0.153532	11.36555	4.432747	0.5241	0.204408	11.96852	4.58048	0.551905	0.21122
6	13.99401	3.285424	0.645306	0.151501	15.47853	4.369447	0.713763	0.201489	16.27788	4.582933	0.750623	0.211333
8	19.4426	3.429523	0.896558	0.158146	20.95507	4.491094	0.966303	0.207098	22.24112	4.795567	1.025606	0.221138
10	23.52082	3.618809	1.084617	0.166874	25.23506	4.658447	1.163666	0.214815	26.16478	4.900234	1.206538	0.225965
12	27.17035	3.928046	1.252908	0.181134	23.75899	6.426651	1.0956	0.296353	29.49274	5.275647	1.360001	0.243276
14	19.30096	7.398416	0.890026	0.341164	20.15291	8.284097	0.929312	0.382005	20.80169	8.86257	0.95923	0.40868
16	18.53497	8.495365	0.854704	0.391747	19.64907	9.179637	0.906079	0.423301	19.91873	9.966171	0.918513	0.459571

Alpha	Flap - 0 degrees			Flap - 5 degrees			Flap - 10 degrees			Flap - 15 degrees		
	Cl	Cd	Cl/Cd	Cl	Cd	Cl/Cd	Cl	Cd	Cl/Cd	Cl	Cd	Cl/Cd
-2	-0.01913	0.220982	-0.08655	0.192554	0.217086	0.886991	0.38186	0.210886	1.810741	0.555559	0.216696	2.56377
0	0.167986	0.218945	0.767254	0.395801	0.215732	1.834687	0.5827	0.214995	2.710299	0.775504	0.220685	3.514076
2	0.373464	0.213235	1.751423	0.600512	0.212022	2.832308	0.801179	0.216225	3.705304	1.001759	0.22684	4.416154
4	0.553398	0.211791	2.61294	0.795292	0.215619	3.688422	0.999652	0.220567	4.532188	1.205684	0.234578	5.139805
6	0.752652	0.211905	3.551847	1.026859	0.221014	4.646118	1.208421	0.223662	5.402888	1.408881	0.242564	5.808277
8	1.028379	0.221736	4.637849	1.25395	0.230227	5.446588	1.434926	0.241845	5.933253	1.628946	0.267488	6.08978
10	1.2098	0.226576	5.339495	1.436283	0.247838	5.795251	1.596569	0.258987	6.164668	1.770041	0.284232	6.227456
12	1.363678	0.243934	5.590356	1.555471	0.265554	5.857459	1.231522	0.431159	2.856307	1.274857	0.488477	2.609863
14	0.961823	0.409785	2.34714	1.065762	0.460787	2.312917	1.13347	0.493161	2.298375	1.212461	0.536495	2.259968
16	0.920997	0.460813	1.998634	1.054174	0.525411	2.006378	1.124108	0.551123	2.039669	1.196094	0.584134	2.047637

	Tail = Alpha		No Tail		Tail = 0 degrees	
Alpha	Cl	Cd	Cl	Cd	Cl	Cd
-2	0.380808	0.210305	0.380234	0.21014	0.401408	0.212924
0	0.581095	0.214403	0.55992	0.211619	0.581095	0.214403
2	0.798972	0.215629	0.780873	0.211286	0.802048	0.21407
4	0.996898	0.21996	0.98428	0.218111	1.005454	0.220895
6	1.205092	0.223046	1.220569	0.22767	1.241744	0.230454
8	1.430973	0.241178	1.43811	0.243275	1.459285	0.246059
10	1.592171	0.258274	1.602536	0.26283	1.623711	0.265614
12	1.228129	0.429971	1.176226	0.45942	1.1974	0.462204
14	1.130347	0.491803	1.083275	0.511669	1.10445	0.514453
16	1.121011	0.549604	1.072487	0.56087	1.093662	0.563654

	With Gap			Close Gap		
Alpha	Cl	Cd	(Cl)^2	Cl	Cd	(Cl)^2
-2	0.382684	0.211494	0.146447	0.507193	0.20239	0.257244
0	0.563528	0.212982	0.317564	0.745157	0.206032	0.555259
2	0.785904	0.212647	0.617645	0.985694	0.205546	0.971593
4	0.990621	0.219516	0.981331	1.212638	0.208468	1.470491
6	1.228433	0.229137	1.509048	1.455606	0.212102	2.118789
8	1.447376	0.244842	2.094897	1.665599	0.222852	2.77422
10	1.612861	0.264523	2.60132	1.844667	0.239904	3.402795
12	1.183804	0.46238	1.401392	1.201443	0.481778	1.443465
14	1.090255	0.514965	1.188655	1.137313	0.52315	1.293482
16	1.079397	0.564484	1.165099	1.138512	0.567873	1.296211

	No Wheels		Wheels #1		Wheels #2		Wheels #3		Wheels #5		Wheels #6	
Alpha	Cl	Cd	Cl	Cd	Cl	Cd	Cl	Cd	Cl	Cd	Cl	Cd
-2	0.328224	0.113655	0.383385	0.211881	0.385831	0.224342	0.390898	0.204563	0.377138	0.173984	0.373075	0.165295
0	0.525158	0.113938	0.56456	0.213372	0.57369	0.221236	0.576442	0.204028	0.573799	0.176611	0.576377	0.168342
2	0.744021	0.116131	0.787344	0.213037	0.81588	0.224021	0.810616	0.205364	0.796157	0.176122	0.787235	0.172263
4	0.962251	0.122162	0.992436	0.219918	1.006713	0.226061	1.04395	0.210431	1.025373	0.18394	1.006644	0.175063
6	1.182217	0.128844	1.230684	0.229556	1.238896	0.233578	1.257134	0.215703	1.232781	0.191147	1.224754	0.180399
8	1.395063	0.143554	1.450028	0.245291	1.458076	0.243912	1.471596	0.229423	1.438113	0.206214	1.43405	0.198609
10	1.562763	0.1635	1.615816	0.265008	1.623253	0.259914	1.617225	0.238258	1.610945	0.224789	1.604622	0.21732
12	1.112281	0.361701	1.185973	0.463227	1.17063	0.425253	1.169604	0.406617	1.168097	0.423389	1.144879	0.416953
14	1.035224	0.414828	1.092252	0.515909	1.084072	0.479812	1.094928	0.463304	1.099023	0.474269	1.081637	0.475187
16	1.023746	0.464262	1.081375	0.565518	1.082958	0.528742	1.086748	0.5256	1.08215	0.529915	1.077749	0.522736

Comparisons
Table lookup vs
Curve fit