Configuration Effects on the Lift of a Body in Close Ground Proximity

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The lift developed by a body moving in close ground proximity can be affected significantly by the shape of the body and its height above the ground. The research described examines some of these effects analytically and obtains a two-dimensional body shape which has a maximum lift under a specific set of constraints. Experimental work which gives confirmation of the analytical technique and provides some insight into the lift developed by a three-dimensional body of small aspect ratio is described. It is shown that, for low heights and proper vehicle geometry, the two-dimensional analytical technique can be used to give an estimate of the three-dimensional pressure distribution. The effects of end plates and of venting around the bottom of the vehicle also are examined, and the importance of minimizing such venting is emphasized.

I. Introduction

OVER the past several years an increasing amount of interest has been focused on the problems of intercity ground transportation for the future. It is expected that, whatever form this transportation system finally takes, it will be capable of speeds up to 400 mph in open air and will travel at heights of less than 0.20 chord and could be within 1 in. of the guideway. As a result, a specially constructed track for support, guidance, and propulsion will be necessary. Considerable time and effort are being devoted to propulsion and support for this type of vehicle,[1,2] but little has been done to use the available aerodynamic forces, such as aerodynamic lift, to best advantage. Aerodynamic lift could be used to augment the lift generated by other means and, thus, to reduce the power necessary to support either of the two most promising vehicle prospects – the Tracked Air Cushion Vehicle (TACV) or the magnetically levitated vehicle. For the case of the magnetically levitated vehicle, the use of aerodynamic lift also may present the possibility of reducing track costs by reducing the support requirements of the magnets or fixed plates used to lift the body. For the TACV, aerodynamic lift augmenting air cushion lift would reduce the power required to compress air for the air cushions. In addition, this effect would reduce significantly the propulsive power required to overcome the momentum drag associated with ingestion of air for the air cushions.

One of the most promising means of developing aerodynamic lift is "ram lift," lift developed when flow beneath the body is properly restricted, giving near stagnation conditions over a section of the lower surface. The combination of high lower-surface pressures and the low pressures on the top of the vehicle gives a net lifting force which can be used to augment other sources of support, or, possibly, to provide complete support.

The use of ram lift to support a vehicle in close ground proximity is not a new idea. Several researchers have made experimental models demonstrating the effect,[3-9] and several others have discussed techniques for calculating the lift generated by some specialized shapes.[5,9-11] Barrows[7] discussed the concept for a vehicle using the ram air cushion for support but did not present quantative data on the lift developed. The analytical techniques described in Refs. 12-19 have had great success in predicting the pressure distribution and lift coefficient on arbitrarily shaped two- and three-dimensional bodies both in and out of ground effect. One of these techniques was selected for this study.

Some of the experimental work mentioned above hinted at an interesting possibility. Results presented by Carter[4] and by Davis and Harris[5] indicated that, for low aspect ratio airfoils with end plates in ground effect, the lift coefficient and pressure distribution could be approximated using two-dimensional aerodynamics for certain end plate geometries and heights. This would, of course, facilitate the analysis of the flow around this type of vehicle.

The research described in this paper was conducted 1) to examine the effects of various shape parameters on the lift developed by a two-dimensional body in close ground proximity, 2) to determine the two-dimensional shape having the maximum lift, under certain constraints on the allowable geometry, and 3) to determine when the two-dimensional approach could be used to estimate the lift and pressure distribution on a low aspect ratio body with end plates. The effects of the shape parameters were determined using the two-dimensional potential flow technique described in Ref. 13-16, and the results are given in Sec. 3. Section 4 describes the optimal shape derived by combining the potential flow method with an optimization technique, and Sec. 5 describes the experimental work performed to check the analytical method for this application and to evaluate various three-dimensional effects as compared to the two-dimensional predictions.

II. Flow Analysis and Body Geometry

The flow around the two-dimensional body was assumed to be inviscid, incompressible, and steady, and the potential flow technique described in Refs. 13-16 was used to determine the pressure distribution and lift coefficient. This technique, which assumes sources and vortices distributed on the surface of the body, was found to give excellent agreement with experimental data for height/chord ratios down to 0.05. Below this height, a modified technique was used.[20]

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Initially, two basic families of body shapes were examined using the potential flow technique. Typical family members are illustrated as configurations A and B in Fig. 1. Configuration C in the figure was added after the optimization process determined that this geometry produced the maximum lift. (The process leading to this conclusion will be described later.) Each of these configurations is defined by the location and radii of the circles shown and by the thickness of the body. A variety of shapes can be generated by manipulating these quantities. Notice that the major difference between configurations A and B is the shape of the bottom of the vehicle. The flat top and sharp trailing edge was common to all body shapes examined.

III. Effect of Body Geometry

The analytical technique was used to determine how various shape parameters affect the lift generated by the two-dimensional bodies described precviously in ground effect. Figure 2 shows that, for a fixed vehicle height h, the lift can be increased by increasing the front channel length L. Figure 3 indicates that the variation of C_L and the location of the center of pressure are functions of the vehicle thickness ratio t/c. Figure 4 demonstrates that the two-dimensional lift coefficient can be increased by increasing the bluntness of the body, and Fig. 5 shows the effect of the difference in channel height on the lift coefficient and center of pressure. It should be noted in reference to Fig. 4 that this analysis assumed no flow separation. The flow over a real vehicle using the rectangular nose shape may separate at the nose,[21] significantly reducing the lift coefficient.

IV. Optimal Two-Dimensional Geometry

The two-dimensional potential flow technique was combined with the "complex method" of optimization described by Box[22] to determine the geometric characteristics of the body having the highest lift coefficient. The body generated was constrained by certain requirements: 1) the thickness/chord ratio must remain at a specified value, 2) the cross-sectional area must remain greater than a specified minimum value, 3) the forebody or nose shape must not be blunt, and 4) the front channel length must remain less than a specified maximum length. The cross-sectional area was limited to insure that the optimization procedure did not produce a very thin body. A blunt forebody was avoided because of the aforementioned danger of flow separation on an actual vehicle.

Figure 6 shows the profile of the body generated by the optimization process and the corresponding pressure distribution. As seen, the body has a semicircular nose, the bluntest allowed, and a front channel which extends nearly the whole vehicle length, the maximum length allowed. In addition, the cross-sectional area has reached the minimum allowed value. (A comparison of the characteristics of this geometry with those of the suboptimal shapes is contained in Figs. 2-5.)

It is important to note that the vehicle produced by the optimization process was formed essentially by adjusting the height and length of the front channel to the maximum values permissible under the constraints imposed. This is in keeping with Figs. 2 and 5, which show that these variations have significant effects on the total vehicle lift.

V. Experimental Work

This section describes the wind-tunnel tests which were made to verify the analytical results described earlier and to obtain pressure distributions on several three-dimensional geometries for comparison with the two-dimensional results. The three-dimensional bodies examined had an aspect ratio of 0.2, and the tests were designed to indicate the effects of end plates, and venting beneath the end plates, on the pressure distribution on the body. Before proceeding to a detailed description of the results of these tests, the two-dimensional tests are described.

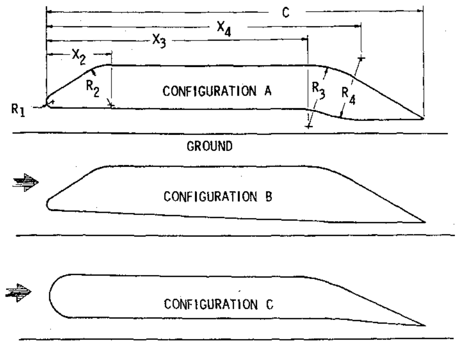


Fig. 1 Families of body shapes considered.

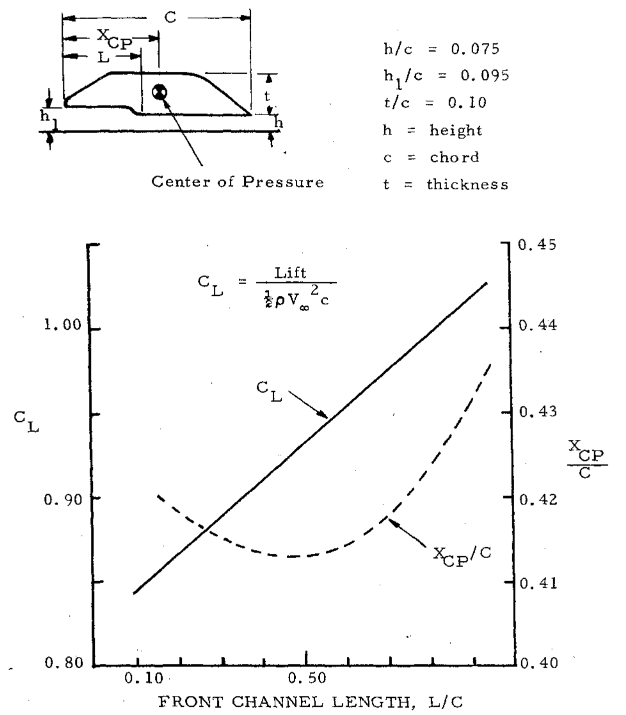


Fig. 2 Effect of front channel length on lift coefficient and center of pressure.

A. Two-Dimensional Body

The profile of the experimental model is shown in Fig. 7. (As seen, this geometry is the same as the optimal geometry described earlier.) The model was instrumented with 90 pressure taps, each connected to a manometer so that the pressure at preselected locations could be determined. The model was tested at velocities of approximately 46 m/sec (150 fps), such that Reynolds number based on a model length of 0.61 m (2 ft) was approximately 1.75×10^6.

As seen in Fig. 8, the image method was used to simulate ground proximity and was expected to give results which would compare well with actual conditions.[23] The splitter plate shown in the figure was used at the trailing edge to insure that there was no mixing of the wakes in the neighborhood of the body. Large end plates were placed on each side of the test body to insure two-dimensional flow.

Figure 9 gives a sample of the experimental results obtained compared with the analytical results for the same height. As seen, the analytic technique gives a good representation of the pressure distribution. (The spanwise pressure taps were used to check for uniformity of flow over the two-dimensional body. The image or symmetric body was instrumented for flow symmetry evaluation.) Similar measurements were made for eight height-to-chord ratios varying from $h/c = 0.005$ to $h/c = 0.2$. The experimental results showed good agreement

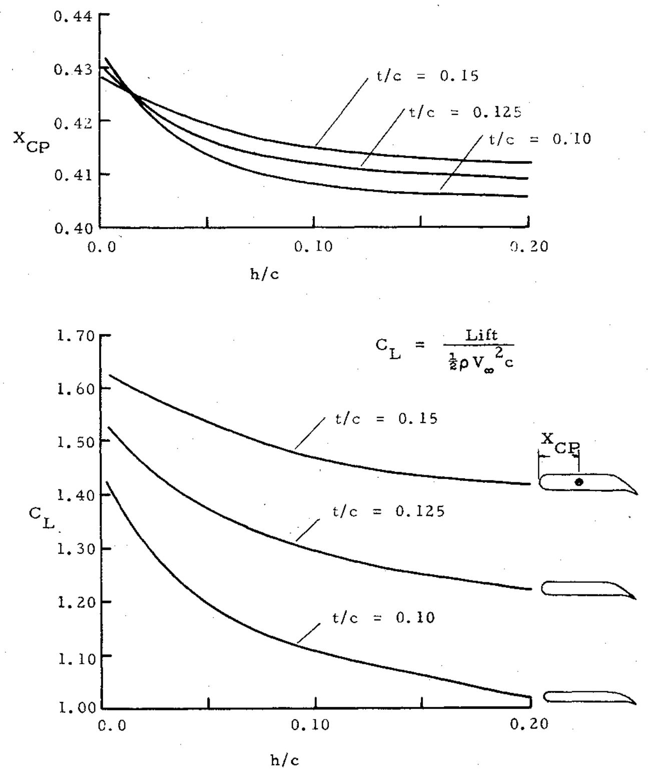


Fig. 3 Effect of body thickness on lift coefficient and center of pressure.

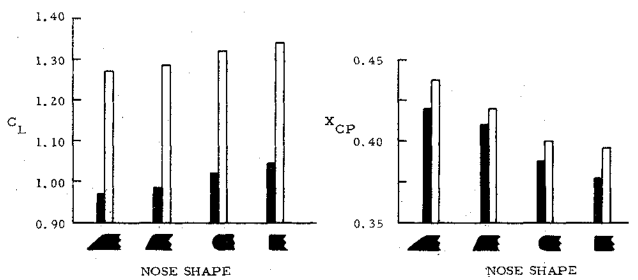


Fig. 4 Effect of nose shape on lift coefficient and center of pressure. $t/c = 0.10$, bottom geometry fixed. □ $h/c = 0.005$, ■ $h/c = 0.075$.

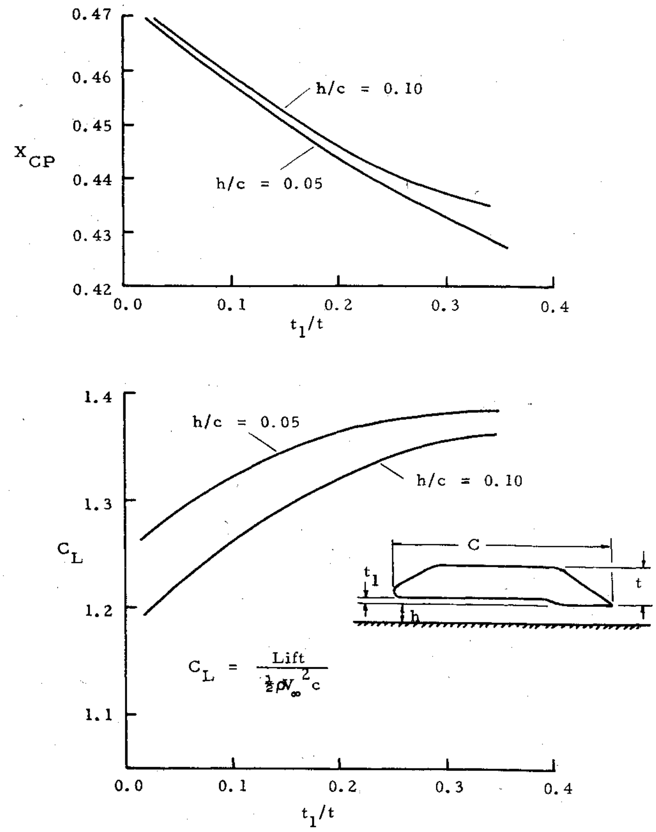


Fig. 5 Effect of channel height on lift coefficient and center of pressure.

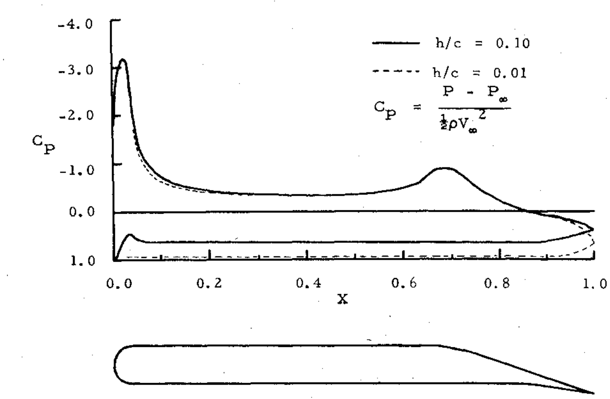


Fig. 6 Pressure coefficient over optimized body shape.

with the analytical results throughout the range of height-to-chord ratios.

B. Body with End Plates

This section describes the experimental model constructed to evaluate the pressure distribution on a three-dimensional body with end plates and presents results obtained. The geometry selected had an aspect ratio of 0.2 and consisted essentially of a slice of the previously described two-dimensional body fitted with end plates of various types. Figure 10 shows the three-dimensional model as it was configured for the wind-tunnel tests. The end plates pictured in Fig. 10 are of the type used by Carter,[4] except that the configuration shown simulates plates which extend to the ground.

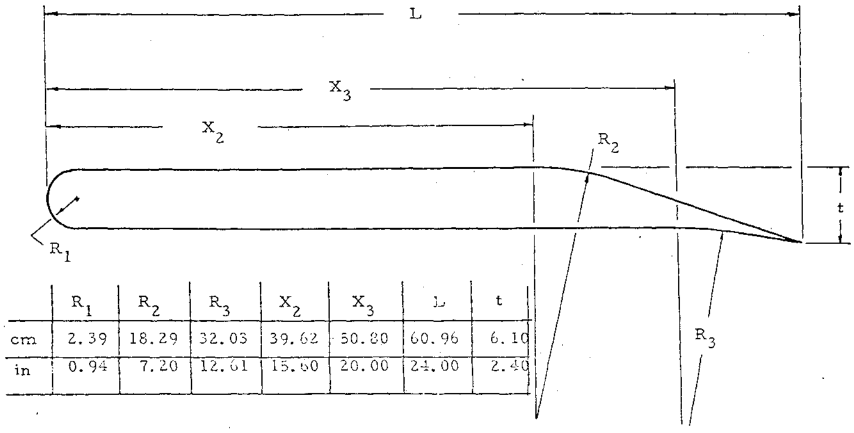
The model and end plate configuration pictured in Fig. 10 were tested at height-to-chord ratios varying from 0.005 to 0.20. Figure 11 shows the results obtained for $h/c = 0.025$. The off-centerline pressures are indicated by the symbols shown.

Figure 12 compares the centerline lift coefficient obtained for the configuration pictured in Fig. 10 with that obtained by the two-dimensional experimental and analytical methods. For heights less than 0.01 chord, the three-dimensional results are approximately 16% less than the two-dimensional measurements.

The end plates pictured in Fig. 13 were an attempt to make the flow over the body more two-dimensional and represent the type of modification possible on an actual vehicle. For $h/c = 0.005$, end plates of this geometry produced a vehicle lift coefficient 11% less than that measured in the two-dimensional tests. The spanwise variation in the lift coefficient for this model is given in Fig. 14. The nearly constant lift coefficient along the span of the body is due in large part to the constant pressure measured in the channel region (see Fig. 13).

C. Vented End Plates

Several tests were run with the end plates modified to allow flow discharge from the sides of the vehicle at the ground surface. This corresponds to the actual vehicle situation where the end plates extend below the body but do not touch the ground. A photograph of the model with the vents completely open is shown in Fig. 15. All of the tests with the vented plates were conducted at $h/c = 0.005$.



	R_1	R_2	R_3	X_2	X_3	L	t
cm	2.39	18.29	32.03	39.62	50.80	60.96	6.10
in	0.94	7.20	12.61	15.60	20.00	24.00	2.40

Fig. 7 Profile of experimental model.

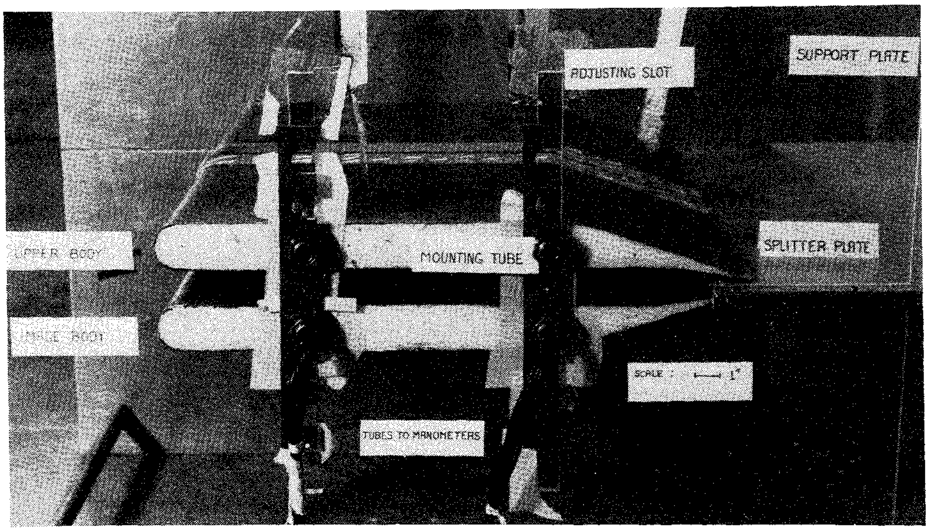


Fig. 8 Experimental model for two-dimensional tests.

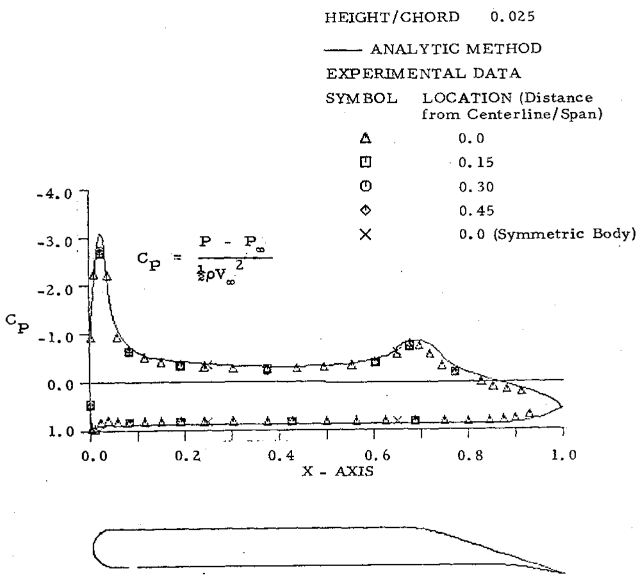


Fig. 9 Sample experimental results.

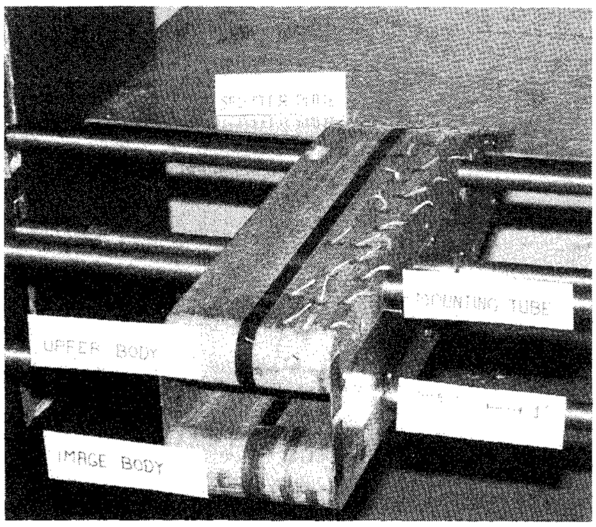


Fig. 10 Low aspect ratio test body.

The results shown in Fig. 16 demonstrate the desirability of reducing the vent area. (The parameter plotted in Fig. 16 is the ratio of the side vent area, given by $A_{sv} = h\ell_{sv}$, to the constant rear vent area $A_{rv} = hw$. The quantity h is the vehicle height, w is the vehicle width, and ℓ_{sv} is the length of the side vent.) As illustrated in the figure, some venting is possible before serious effects on the lift coefficient are observed.

Figure 17 compares the experimentally determined lift coefficients for the various end plate configurations with the two-dimensional experimental and analytical results. The notation "3-D model" refers to the configuration shown in Fig. 10, whereas the model with the modified end plates is that pictured in Fig. 13. The comparison was constructed for $h/c = 0.005$, and clearly shows the value of the end plates in increasing the lift coefficient.

VI. Conclusions

The analytical study has shown how the lift coefficient of a two-dimensional body in ground effect is affected by the

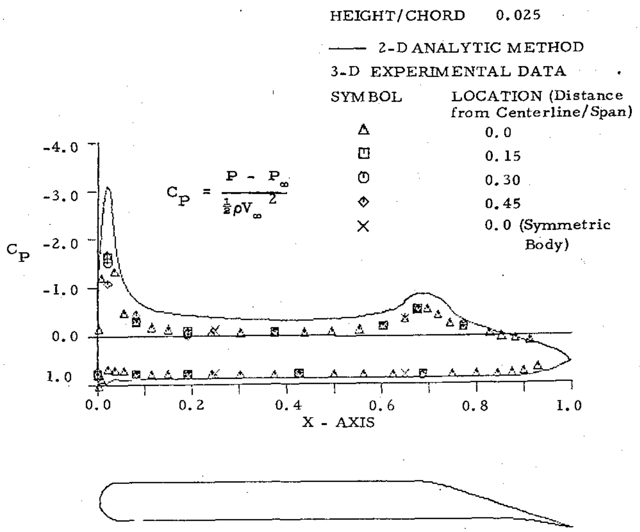


Fig. 11 Sample data from low aspect ratio test body.

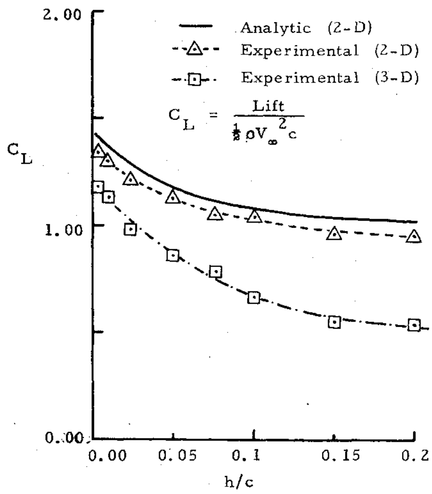


Fig. 12 Comparison of analytical and experimental lift coefficients.

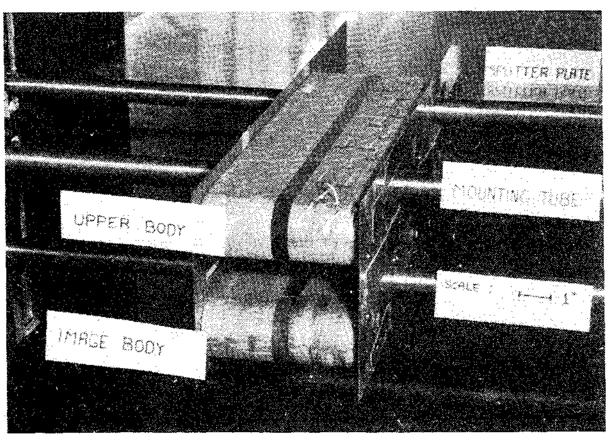


Fig. 13 Experimental model with end plates extended above the model.

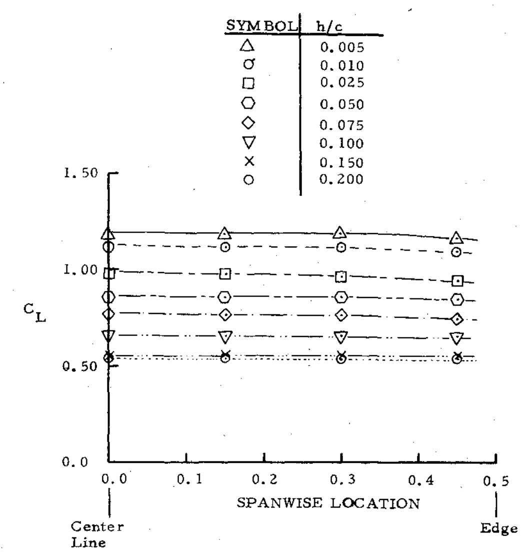


Fig. 14 Spanwise variation of lift coefficient.

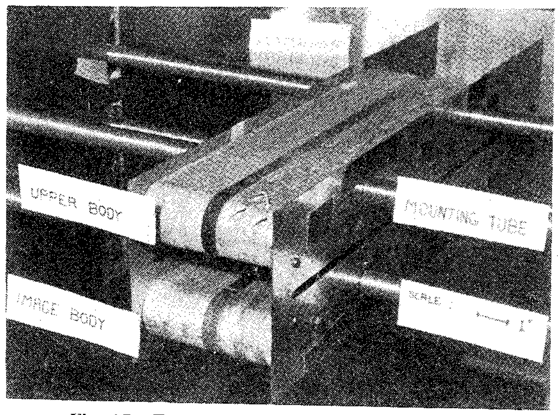


Fig. 15 Test model with vented end plates.

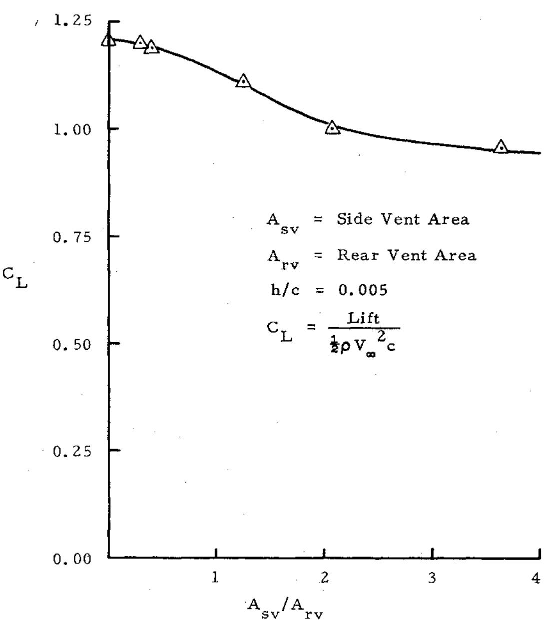
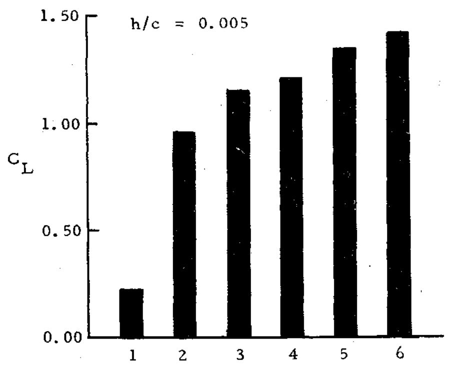


Fig. 16 Effect of side vent area on lift coefficient.

shape and thickness of the body. The geometry of the bottom of the body is seen to have the greatest effect on the total lift, and the shape of the nose can be adjusted to augment the lift arising from the high pressure on the lower surface. The maximum lift coefficient is obtained for a geometry having a blunt nose and a front channel which extends as far to the rear as possible.

The experimental investigation of the pressure distribution on a body with end plates has shown, for low heights and for a body of the type described with minimal venting beneath the end plates, that the pressure distribution over such a body can be approximated by the pressure distribution on a two-dimensional body of equivalent cross-sectional geometry. The



No.	CONDITIONS
1.	No End Plates
2.	Model With Vented End Plates -- Vents Open
3.	3-D Model
4.	Model with Modified End Plates
5.	2-D Experimental
6.	2-D Analytical

Fig. 17 Summary of lift coefficient results for end plate configurations tested.

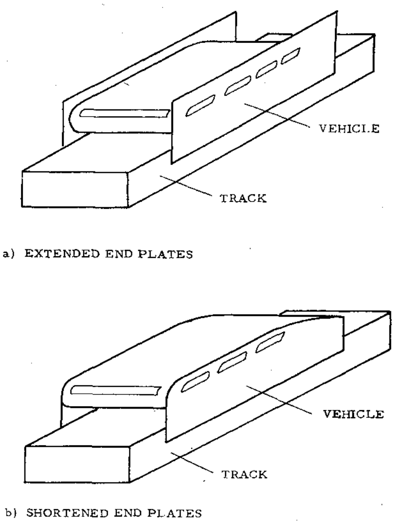


Fig. 18 Vehicle configurations using the vehicle body to augment lift.

use of end plates which extend above the body improves this approximation.

In summary, this research has verified that significant amounts of lift can be generated by a properly shaped vehicle moving in close ground proximity. The results indicate the importance of the nose and underbody shapes in determining the resulting vehicle lift. In addition, the use of end plates on a low aspect ratio body significantly increases the lift developed, and, as the flow discharge beneath the end plates is reduced, the pressure distribution over the body more closely approximates the two-dimensional pressure distribution.

These conclusions apply to the design of full-scale vehicles using ram lift for a portion or all of the required lifting force. A vehicle configured for maximum lift will have end plates of the types described here, and Fig. 18 illustrates two possible geometries. The vehicles have a semi-circular nose and a constant profile over the width.

References

[1]Yaffie, M. L., "Magnetic Vehicle R&D Spurred," *Aviation Week and Space Technology,* Vol. 97, July 10, 1972, p. 47.

[2]Kolm, H.H. and Thornton, R.D., "Electromagnetic Flight," *Scientific American,* Vol. 229, Oct. 1973, pp. 17-25.

[3]Kaario, T. J., "Process for Eliminating Friction Between a Surface Vehicle and the Surface," Finnish Patent No. 18630, 1935.

[4]Carter, A. W., "Effect of Ground Proximity on the Aerodynamic Characteristics of Aspect Ratio 1 Airfoils with and Without End Plates," NASA TN-D 970, 1961.

[5]Davis, J. E. and Harris, G. L., "Nonplanar Wings in Nonplanar Ground Effect," *Journal of Aircraft,* Vol. 10, May 1973, p. 308.

[6]Gallington, R. W. and Miller, M. K., "The Ram Wing: A Comparison of Simple One-Dimensional Theory with Wind-Tunnel Tests and Free Flight Results," AIAA Paper 70-971, 1970.

[7]Barrows, T. M., "The Ram Air Cushion-Advanced Fluid Suspension for Tracked Levitated Vehicles," ASME Publication 73-ICT-14, 1973.

[8]Barrows, T. M., "Progress on the Ram Wing Concept with Emphasis on Lateral Dynamics," Department of Transportation, Washington, D.C., Technical Report DOT-TSC-FRA-71-7, 1971.

[9]Davis, J. E., "Non-Planar Wings in Non-Planar Ground Effect," Ph.D. thesis, 1971, California Institute of Technology, Pasadena, Calif.

[10]Widnall, S. E. and Barrows, T. M. "An Analytic Solution for Two- and Three-Dimensional Wings in Ground Effect," *Journal of Fluid Mechanics,* Vol. 41, Pt. 4, 1970, p. 469.

[11]Royce, W. W. and Rethorst, S., "Translational Characteristics of Ground Effect Machines," IAS Paper No. 61-79, 1961.

[12]Bagley, J. A., "The Pressure Distribution on Two-Dimensional Wings Near the Ground," Aeronautical Research Committee, R&M 3238, 1960.

[13]Smith, A. M. O. and Pierce, J., "Exact Solution of the Neumann Problem. Calculation of Non-Circulatory Plane and Axially Symmetric Flow About or Within Arbitrary Boundaries," Douglas Aircraft Company, Los Angeles, Calif. Rept. ES26988, 1958.

[14]Hess, J. L. and Smith, A. M. O., "Calculation of Potential Flow About Arbitrary Bodies," *Progress in Aeronautical Sciences,* Vol. 8, Pergamon Press, New York, 1967, p. 1.

[15]Giesing, J.P., "Potential Flow About Two-Dimensional Airfoils. Part 1: A Summary of Two-Dimensional Airfoil Methods. Part 2: Solution of the Flow Field About One or More Airfoils of Arbitrary Shape in Uniform or Nonuniform Flows by the Douglas Neumann Method," Douglas Aircraft Company, Los Angeles, Cal., Rept. LB31946, 1965.

[16]Giesing, J.D., "Potential Flow About Arbitrary Three-Dimensional Lifting Bodies," Douglas Rept. MDC-J5679-01, Oct. 1972, Doglas Aircraft Co.; also published as "The Problem of Three-Dimensional Lifting Potential Flow and Its Solution by Means of Surface Singularity Distributions," *Computer Methods in Applied Mechanics and Engineering,* Vol. 4, Nov. 1974.

[18]Rubbert, P. E. and Saaris, G. R., "Review and Evaluation of a Three-Dimensional Lifting Potential Flow Analysis Method for Arbitrary Configurations," AIAA Paper 72-188, Jan. 1972.

[19]Johnson, F. T. and Rubbert, P. E., "Advanced Panel-Type Influence Coefficient Methods Applied to Subsonic Flows," AIAA Paper 75-50, Jan. 1975.

[20]Ailor, W. H., "Shape and Thickness Effects on the Lift Developed by a High Speed Ground Transportation Vehicle Using Ram Air For Support," Ph. D. thesis, Purdue Univ., West Lafayette, Ind., Aug. 1974.

[21]Schlichting, H., *Boundary Layer Theory,* McGraw-Hill, New York, 1962.

[22]Box, M. J., "A New Method of Constrained Optimization and a Comparison with Other Methods," *The Computer Journal,* Vol. 8, 1965, p. 42

[23]Grunwald, K. J., "Aerodynamic Characteristics of Vehicle Bodies at Crosswind Conditions in Ground Proximity," NASA TN D-5935, 1970.