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A STUDY OF AUTOMOTIVE AERODYNAMIC DRAG

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16. Abstract

Reductions of aerodynamic drag in the 20-25% range through the use of several established drag-reduction devices and minor design changes have been demonstrated on three large sales-volume 1974 and 1975 model American automobiles. Comparisons of test techniques were made by testing one automobile both full-scale and as a 0.4-scale model in two different wind tunnels. Another vehicle was tested both full-scale in a wind tunnel and by the coast-down technique. Good comparative results were obtained.

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PREFACE

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A window fairing at top of windshield, top of front door and around A-post (see Figure 3-1)

D3 front dam, 6-inch ground clearance at centerline (see Figure 3-2)

D9 front dam, 8.5-inch ground clearance at centerline (see Figure 3-6)

L hard trunk deck-base intersection at 90 degrees (see Figure 3-3)

L1 2-inch high spoiler, 90 degrees to trunk deck surface near rear radius (see Figure 3-4)

N1 long nose modification extending 11.25 inches (full scale) beyond bumper (see Figures 2-1 and 2-2); tested on 0.4-scale) Mustang II only

N2 short modified nose (see Figure 2-4)

P1 underpan extending to rear axle, tested only on full-scale Impala and Mustang II model

P2 underpan extending only to firewall

ANGULAR MEASUREMENTS

α geometrical angle of attack of the model reference plane; α is positive when the front end of the model is raised, aft end lowered

ψ angle of yaw of the model plane of symmetry (vertical centerplane) relative to a vertical plane through the wind tunnel test section axis; ψ is positive when the front end of the model is moved to the right as viewed by the driver

GEOMETRICAL PARAMETERS

A projected frontal area of the model basic configuration

b wheelbase of the model basic configuration

AIRFLOW PARAMETERS

Equivalent free airstream conditions are defined by the pressure, density, and temperature that an observer at rest at infinity would measure if the model were moving at uniform velocity V through an infinite fluid at rest at infinity.

- q dynamic pressure of equivalent free airstream = $\rho V^2/2$
- V velocity of equivalent free airstream
- R Reynolds number = $\rho Vb/\mu$
- μ absolute viscosity of air
- ρ mass density of air

FORCE AND MOMENT COEFFICIENTS

The following coefficients are referred to the stability axes. Stability axes are defined as orthogonal axes having, at zero yaw, the same direction and signs as the wind axes (wind axes remain fixed with respect to the relative wind), but differing from the latter in that they rotate with the model in yaw. Directions are defined as a driver, sitting in the vehicle, would see them.

C_D stability axis drag coefficient = stability axis drag/qA (C_D is positive when it acts in a direction which coincides with the relative wind at zero yaw, but rotates in yaw with the model)

C_C stability axis cross-wind force coefficient = stability axis cross-wind force/qA (C_C is positive when it acts to the right, perpendicular to the model plane of symmetry)

C_l stability axis rolling moment coefficient = stability axis rolling moment/qAb (C_l is positive when it tends to lower the right ride of the model)

C_L lift coefficient = lift/qA (C_L is positive when it tends to lift the model)

C_m stability axis pitching moment coefficient = stability axis pitching moment/qAb (C_m is positive when it tends to raise the front end of the model)

C_n yawing moment coefficient = yawing moment/qAB (Cn is positive when it tends to move the front end of the model to the right)

For C_l, C_m, and C_n moments are referred to a point in the plane of the model vertical centerplane midway between front and rear axles at the tunnel floor.

1. INTRODUCTION

1.1 SUMMARY

The effects of a number of add-on devices and minor design changes on drag reduction and other aerodynamic characteristics of three large sales volume American automobiles were examined by means of various experimental techniques. Limited testing was carried out with a 0.4-scale model of a 1974 Mustang II notchback coupe in the GALCIT 10-ft wind tunnel. All three cars were tested full-scale in the Lockheed-Georgia Low-Speed Wind Tunnel. One of the cars, a 1975 Chevrolet Impala Sport Sedan, was road tested using a coast-down technique. Each of the three tests is discussed and data presented in separate sections of the report. The findings are summarized below:

1. Comparisons between sub-scale and full-scale wind tunnel test results are presented near the close of the full-scale test section and comparisons between the full-scale wind tunnel test and the road test are also included in this report.
2. General conclusions and recommendations are contained in two final sections. Drag reductions in the range from 20-25% were achieved.
3. Good agreement between the single-point comparisons of test techniques are shown for properly corrected data. The level of agreement may have been fortuitous or hold only for the particular configurations and facilities compared since corrections applied to the various data sets were greater than the differences between the sets.

1.2 PURPOSE

The Automobile Aerodynamic Drag Reduction Program has the following general purposes:

(1) To demonstrate that a significant decrease in the aerodynamic resistance of automobiles can be practically achieved.

(2) To provide the necessary means to include aerodynamic considerations in the development and design cycle of automobiles.

(3) To develop the techniques necessary to quantify the aerodynamic resistance of actual automobiles.

This is the final report of this program, a 9-month effort which began August 5, 1974, and is funded for $55,000. The purpose of the program is:

> To experimentally validate that a reduction in aerodynamic drag is possible through add-on devices and minor design changes to existing types of automobiles with the overall goal of reducing fuel consumption.

1.3 OBJECTIVE

The specific objective is to demonstrate that a 20-25% reduction in aerodynamic drag can be achieved in a practical manner. Based on a 55-45 mix of the EPA urban cycle and highway cycle, a decrease in overall fuel consumption of approximately 5% can be expected when the goal is reached. This amounts to about 3.3 billion gallons or 79 million barrels (at 42 gal/bbl) of gasoline per year for a 100-million-car fleet, assuming 10,000 miles per year at 15 miles per gallon.

1.4 LITERATURE SEARCH

A search of the open literature on automotive aerodynamics and related subject areas culminated in an informal report to the Transportation Systems Center and a bibliography, which was organized under the following subject headings:

Aerodynamics
Cooling Systems

Engine Performance
Fuel Economy
General, Books, Proceedings
Noise
Stability and Handling
Facility Test
Road Test
Tires and Rolling Resistance.

1.5 STATE-OF-THE-ART REPORT

The results contained in the informal report can be summarized as follows: reliable drag data on modern American automobiles available in the open literature has always been very scarce. The Motor Industries Research Association (MIRA) has, in a continuing series of reports, measured in their wind tunnels drag coefficients on some British, European, and American cars dating back to 1926. The mean drag coefficient for the tested American cars in the 1960 to 1965 model years is given as 0.465 (0.421 to 0.510) for the radiator-open case. Equivalent values for British and European cars were 0.452 and 0.433, respectively. While the use of these values as absolute numbers may be inadvisable,[1] their relative magnitudes can be used and indicate that, for the cars tested, the American models showed consistently higher drag than either the British or European models. A tendency for the drag to increase slightly with time was also noted.

A quantitative estimate of the effects of various drag-reduction measures is a somewhat uncertain business; however, some values based on the experimental results of numerous earlier investigations have been tabulated in Table 1-1. Items from the table can be considered additive if only one entry from item 6 is used. The exact values of the increments are, of course, dependent on the baseline design to which they are applied.

[1] Although self-consistent, drag data from the MIRA wind tunnels is persistently slightly lower than equivalent data obtained in a number of American wind tunnels. These differences are thought by American automobile aerodynamicists to be due to differences in testing techniques, but the matter is still an open question at this time. The reader is therefore cautioned against making direct comparisons between MIRA and American drag data, although relative and incremental values of MIRA data are very useful.

TABLE 1-1. DRAG IMPROVEMENT POTENTIAL

Change[a]	ΔC_D, %
1. Interference or parasite drag	4-9
2. Increased front-end radii	5-10
3. Windshield slope and fairing	3-6
4. Rear deck and window modification (fastback = 11%)	5-7
5. Engine cooling	1-2
6. a. Full underpan	15
b. Underpan to front axle	9
c. Front underbody dam	9

[a]Relative to typical 1975 notchback sedan.

It must be recognized that many elements in the design of an automobile are of greater importance to the manufacturer than are the aerodynamics. Therefore, any proposed changes to a design for the purpose of improving the aerodynamic performance of the vehicle must be subject to scrutiny as to their effects on such other design factors as produceability, styling, packaging, and operation in terms of both safety and handling. Although experts in none of these areas were kept in mind in choosing the devices and modifications to be tested.

1.6 PROJECT ELEMENTS

The elements of the project are diagrammed in Figure 1-1. The subscale wind tunnel test shown in the figure was run in the GALCIT[2] 10-foot Wind Tunnel in Pasadena, California, using a 40% scale model of a 1974 Mustang II notchback coupe loaned to the program by the Ford Motor Company. The model was tested with two modified noses, full and partial underpans, front underbody dams (skirts), and rear trunk spoilers. The latter two items were partially optimized for drag effect by varying skirt ground clearance and spoiler height, respectively. Car attitude and ground clearance were varied. Reynolds number effects were investigated and found to be insignificant in the range of road operation. All data were taken within this range. The purpose of this test was to do a preliminary investigation of the geometry and location of some of the drag reduction devices and also to secure data on a subscale model of a car which was to be tested full-scale in a wind tunnel.

The full-scale wind tunnel test shown in the project elements diagram (Figure 1-1) was run at the Lockheed-Georgia Low-Speed Wind Tunnel in Marietta, Georgia, on the 1975 Chevrolet Impala sport sedan, the 1975 Plymouth Valiant 4-door sedan, and the 1974 Ford Mustang II notchback coupe. These cars were chosen as large sales volume representatives of current American cars in the standard, compact, and subcompact size classes. A 1974 Mustang II was tested rather than

[2]Graduate Aeronautical Laboratory, California Institute of Technology.

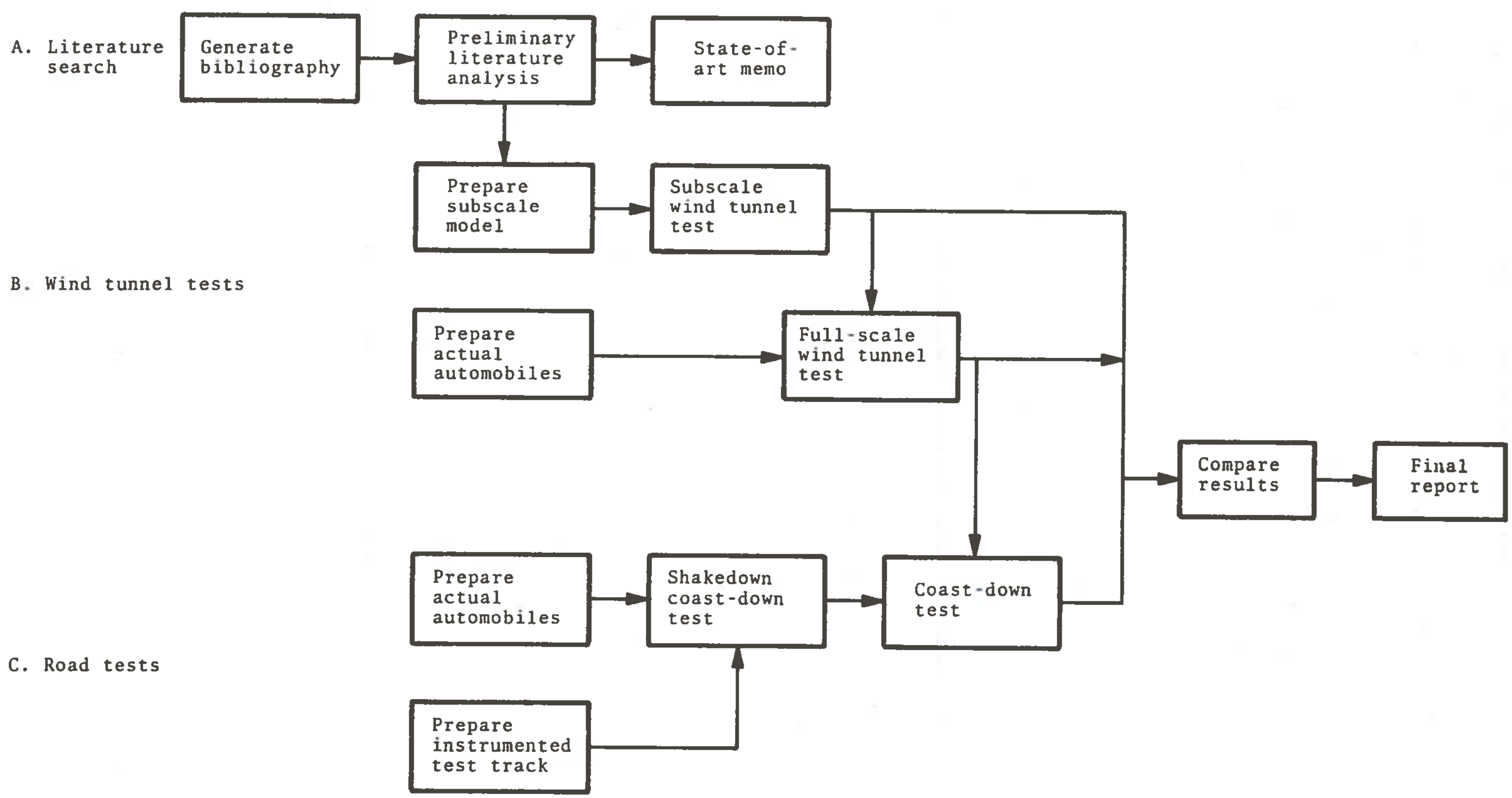

Figure 1-1. Project Elements

a 1975 model in order to match the 0.4-scale model available on loan from the Ford Motor Company. The standard configuration of each car was tested in an off-the-floor condition except that a front license plate, not used in Georgia, was added in the location provided by the manufacturer.

The coast-down test series was carried out from mid-January to mid-February 1975 on the Barrier Test Facility runway at Edwards Air Force Base, California. Eighteen shake-down and thirty final run were made on a standard and a low-drag (N2/D3/L) configuration of a Chevrolet Impala sport sedan.

2. GALCIT WIND TUNNEL TEST

2.1 INTRODUCTION

A 0.40-scale wood model of the 1974 Ford Mustang II, notchback version, on loan from the Ford Motor Company was tested (GALCIT Test 952) in the GALCIT 10-foot Wind Tunnel for the purpose of obtaining basic aerodynamic data on unmodified and reduced-drag configurations. These data were to be compared with data from similar configurations on a full-size Mustang II tested in the Low-Speed Wind Tunnel at Lockheed-Georgia. A total of 52 runs were made over a period of 3 days.

2.2 TEST INSTALLATION

The model was supported above a fixed plate ground plane, which spanned the wind tunnel test section and incorporated a flush, 64-inch-diameter yawtable. Model support consisted of four struts which passed through cutouts in the model wheels and through holes in expendable plates located in the yawtable surface connecting the model to a six-component strain gage balance secured within the yawtable assembly. The balance assembly was windshielded from the airstream by the ground plane enclosure and the support struts were windshielded by the model wheels. This support system provides completely interference-free model support. The model installation is shown in Figures 2-1 and 2-2.

2.3 MODEL

Incorporated in the design of the model used for these tests were wheels which were cut flat across the bottoms. Sponge pads were cemented to these flats to prevent airflow between the wheels and ground plane. The free plane of the sponge pads was representative of static tire deflection. The model was reasonably complete in underbody detail (see Figure 2-3) and included provisions for simulating engine-cooling airflow. The engine-cooling airflow was simulated by appropriate ducting between the grille opening and the underbody, with the engine block and other components represented

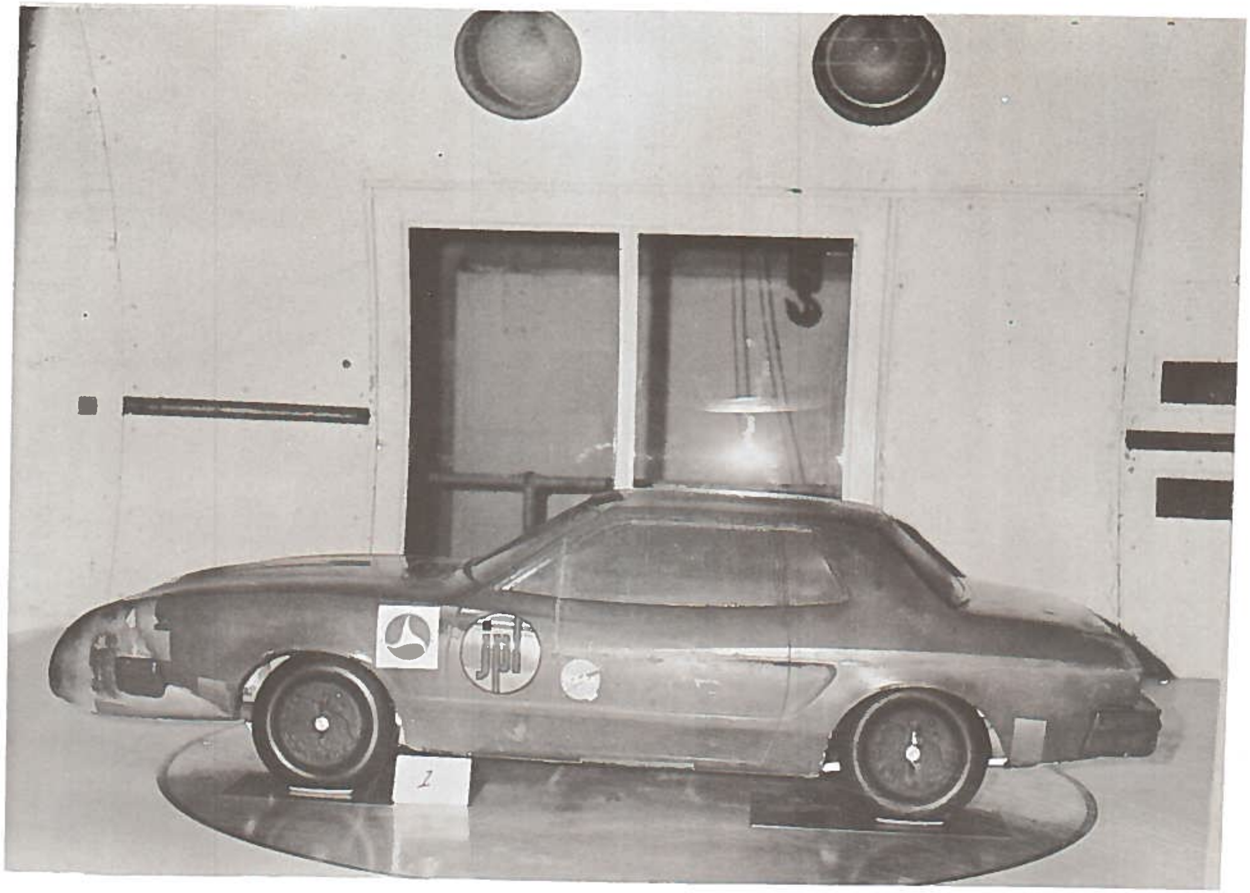

Figure 2-1. Side view of 0.4-Scale 1974 Mustang II Model in N1/P1/- Configuration Installed in GALCIT 10-Foot Wind Tunnel

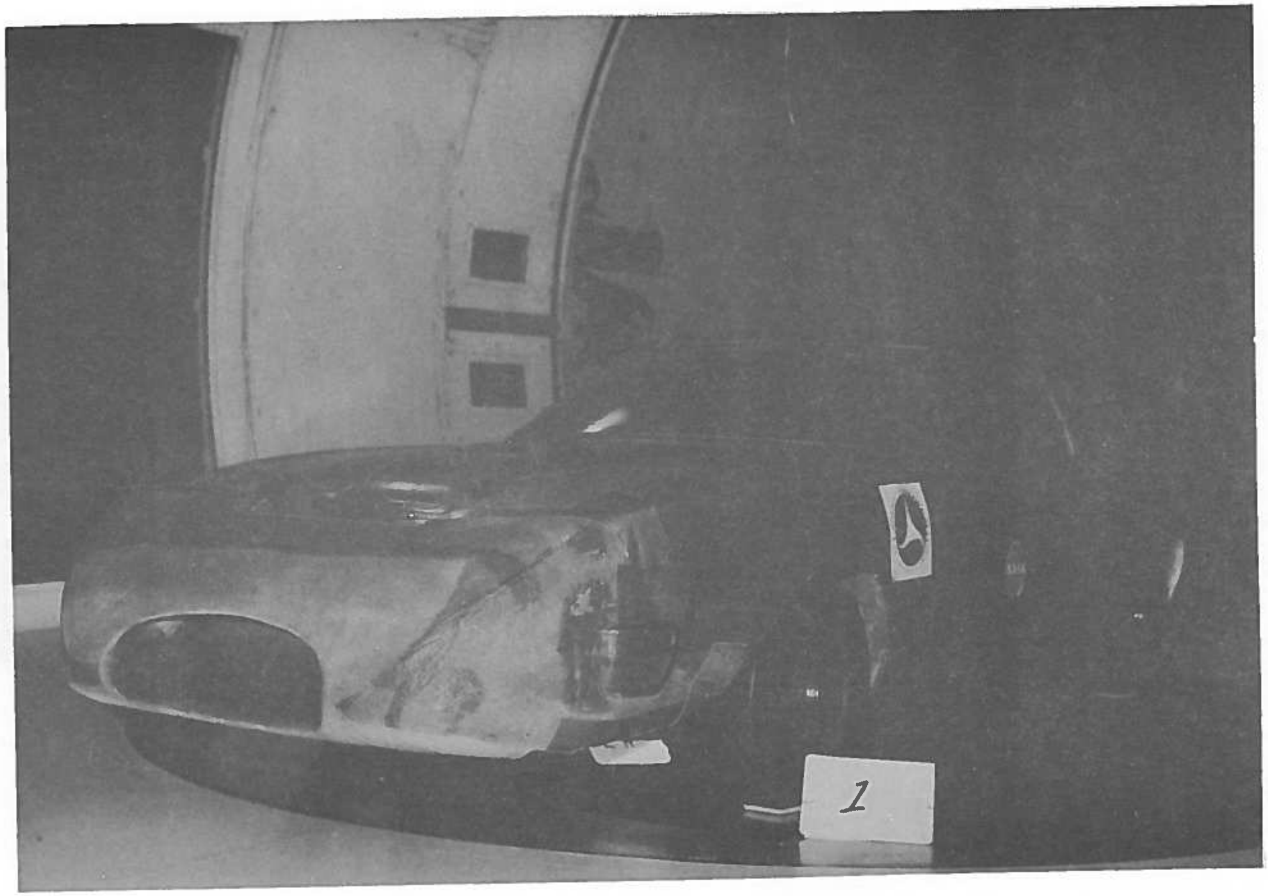

Figure 2-2. Front View of 0.4-Scale 1974 Mustang II Model in N1/P1/- Configuration Installed in GALCIT 10-Foot Wind Tunnel

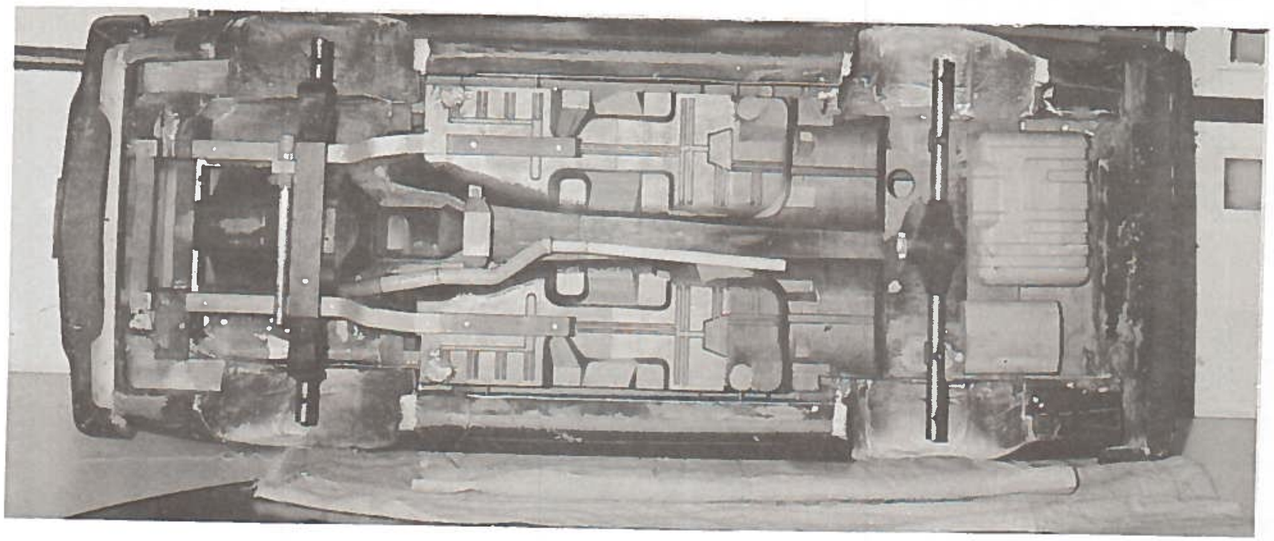

Figure 2-3. View of Underbody Detail on Mustang Model in GALCIT 10-Foot Wind Tunnel

in the engine compartment. A pressure drop across the radiator station was attained by placing a single thickness of fine mesh screen across this station. No provisions were made, however, to measure the cooling airflow rate. In addition, upperbody details, such as windshield wipers, door handles, and trim molding, were absent and no provisions were made to rotate the model wheels. The model was used as received from the Ford Motor Company (minor touchup was carried out) except that a new set of wheels were cast from plastic using the originals as molds. These new wheels were vertically slotted so that the attitude and clearance of the model could be adjusted by moving the axles in the slots.

2.4 DATA REDUCTION

Data recorded during these tests included six-component force and moment data. These raw data were acquired simultaneously for each data point and recorded automatically on IBM cards. The data were then reduced to the final coefficient forms defined in the nomenclature section by an electronic computer. Model configuration nomenclature is defined in that section also. Model dimensional data used for the final coefficients are presented in Table 2-1.

All force and moment data have been corrected for the effects of model solid and wake blocking, of horizontal buoyancy, and of streamline curvature, caused by the presence of the wind tunnel walls. The boundary layer on the ground plane, and nonrotating wheels have not been accounted for.

A review of the data acquired during these tests suggests that the precision of the data, as indicated by repeatability, is generally within the following limits:

ΔC_L ± 0.004: (Δ Lift Coefficient)

ΔC_D ± 0.0014: (Δ Stability Axis Drag Coefficient)

ΔC_m ± 0.0010: (Δ Stability Axis Pitching Moment Coefficient)

ΔC_1 ± 0.0010: (Δ Stability Axis Rolling Moment Coefficient)

ΔC_C ± 0.004: (Δ Stability Axis Cross-Wind Force Coefficient)

ΔC_n ± 0.0010: (Δ Yawing Moment Coefficient)

TABLE 2-1. MODEL DIMENSIONAL DATA USED IN DATA REDUCTION

Reference area (cross section)	3.090 ft^2
Wheel base	3.2083 ft
$X_{cg} = b/2$	1.6042 ft
Z_{cg}	0

The above includes the effects of returning the model to a given configuration after a model change had been made.

The effects of Reynolds number on the standard configuration and on N1/D4/L, a reduced-drag configuration, were investigated by running at varying tunnel velocities which corresponded to a range of Reynolds numbers from 1.69 to 3.78 x 10^6. For all coefficients, uniform values were obtained for Reynolds numbers 2.93 x 10^6. For comparison, the Reynolds number for the full-scale vehicle traveling at 55 mph under the same atmospheric conditions as existed in the wind tunnel would 4.39 x 10^6. This is not far above the maximum test Reynolds number of 3.78 x 10^6, and the data do not suggest that any significant Reynolds number effects would be encountered between the Reynolds number of 3.38 x 10^6 used for the majority of these tests and the full-scale highway Reynolds number.

2.5 TEST RESULTS

Dimensional checks were performed to ensure that the data from the unmodified model were as representative of the road vehicle as the model representation of vehicle would permit. These checks revealed that the overall height of the model roof was 0.3 inch (full scale) too low, while the lower edges of the rocker panels were 0.3 inch (full scale) too high when compared to specifications supplied by Ford. Measurements to the rocker panels, however, are difficult to reproduce because the lower edge is not well defined with curvature in two planes. In addition, the placement of the standard underbody dam on the model was suspected of being in error. Measurements on a 1974 Mustang II were used to locate the standard configuration dam on the model. These measurements were assumed to be the best representation of the actual vehicle geometry and were used during these tests as the standard configuration.

Table 2-2 summarizes the longitudinal data for the more significant configurations tested. The shapes of the curves for these coefficients when plotted versus yaw angle are very similar to those shown in Figures 3-9 and 3-10 from the Lockheed-Georgia tests (presented in the next section), as are the lateral coefficients. In this test,

TABLE 2-2. SUMMARY OF GALCIT 10-FOOT WIND-TUNNEL TEST RESULTS

Item	Configuration	C_D	C_L	C_m	ΔC_D	$\Delta C_D/C_{D(STD)}$
1	Standard	0.469	0.503	0.144	-0-	-0-
2	N2/-/-	0.459	0.553	0.143	0.010	2.1
3	N2/D9/-	0.416	0.502	0.069	0.053	11.3
4	N2/D9/L1	0.382	0.310	0.155	0.087	18.6
5	N2/D9/L	0.380	0.376	0.132	0.089	19.0
6	-/D9/-	0.438	0.479	0.091	0.031	6.6
7	-/D9/L1	0.408	0.327	0.157	0.061	13.0
8	N1/-/L	0.395	0.471	0.181	0.074	15.8
9	N1/P1/-	0.383	0.544	0.183	0.086	18.3
10	N1/P2/-	0.403	0.587	0.137	0.066	14.1
11	N1/P2/L1	0.370	0.387	0.234	0.099	21.1
12	N1/P2/L	0.369	0.466	0.203	0.100	21.3

a nose configuration (N1), extending 11.25 inches forward of the standard nose leading edge as shown in Figure 2-1 and 2-2, was tested together with a full underpan and gave a drag reduction of 21.3% when combined with a squareback (item 12 in Table 2-2). This configuration was tested in model scale to learn what could be done with somewhat more radical but at least marginally practical modifications, although it was in no way optimized. The configuration was not tested full-scale because of limitations on both construction and test time.

Some optimization work on the ground clearance of the front dam and the height of the rear spoiler was done during the test. An example of a front dam configuration is shown in Figure 2-4. The results are shown in Figure 2-5 at zero yaw but also hold in the yaw range from 0 to 18 degrees. It is noteworthy that a rather sharp optimum exists in the vicinity of 8.5-inch dam ground clearance for the configuration and location tested and that this clearance is about equal to minimum ground clearance without the dam. For the rear spoiler configurations tested, a more gradual optimum in the range of 2-to 3-inch height exists. However, the two points not on the curve indicate drag values for a squareback (L) and a squareback with a 1-inch-high spoiler at the rear corner (L + L1), which are lower than the best spoiler height located at the rear edge of the trunk. This suggests that spoiler location should also be optimized. The results of these optimization studies conducted on the Mustang II but were also applied to the Impala and the Valiant tested full-scale at Lockheed-Georgia, since individual optimization was not feasible during the full-scale test and the nose shapes were roughly similar aerodynamically. There is no reason to expect the optimum to hold for the Impala and Valiant, but it was expedient to use common apparatus among all cars as far as possible during the full-scale test.

The simplest modifications to an existing automobile, in this case the 1974 Mustang II notchback, involve replacing the existing dam with a more effective dam and adding a piece of sheet metal to the deck trailing edge for the purpose of reducing aerodynamic drag. It should be noted that moving the dam forward of the more typical production dam location will generally increase the cooling capacity

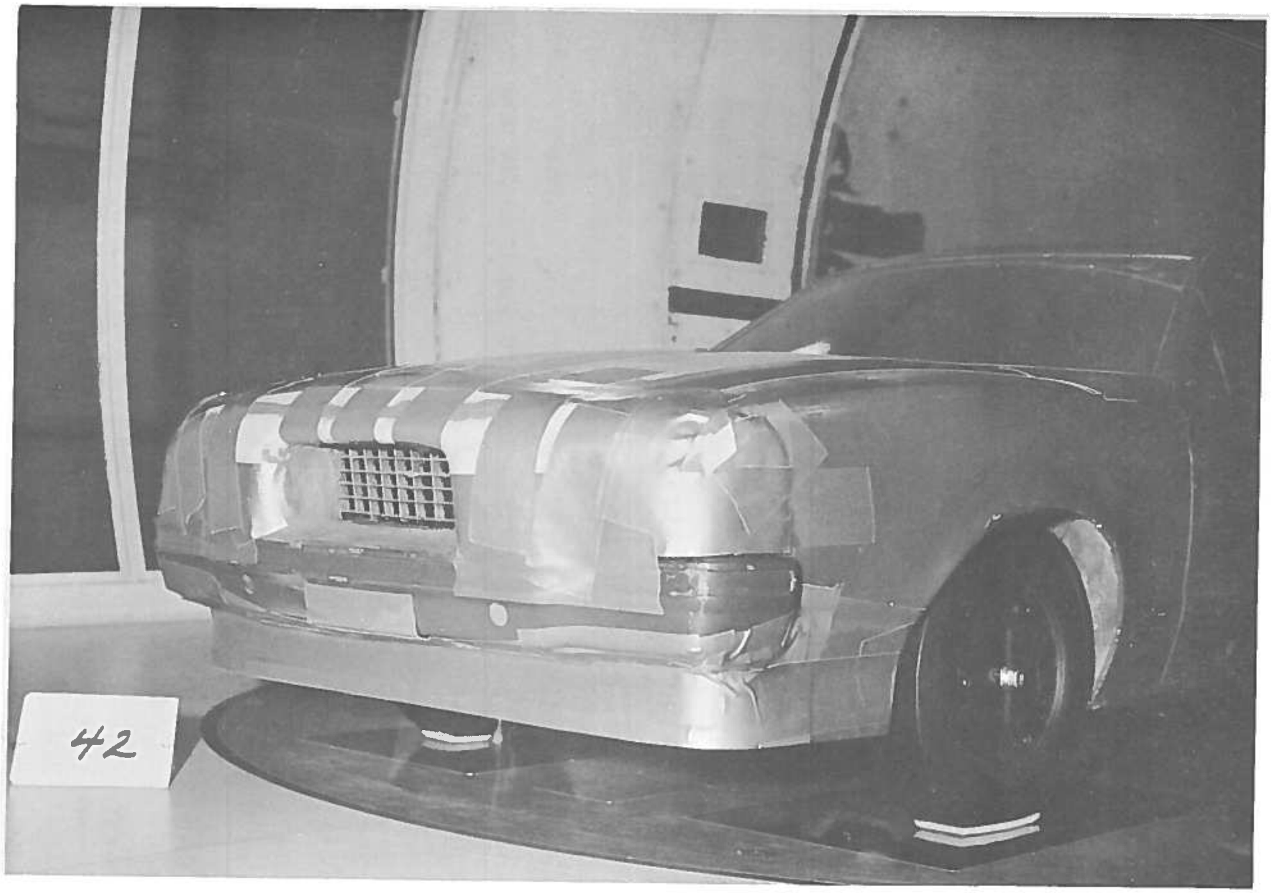

Figure 2-4. Front View of D9-Dam on Mustang II Model Used in Optimization Study

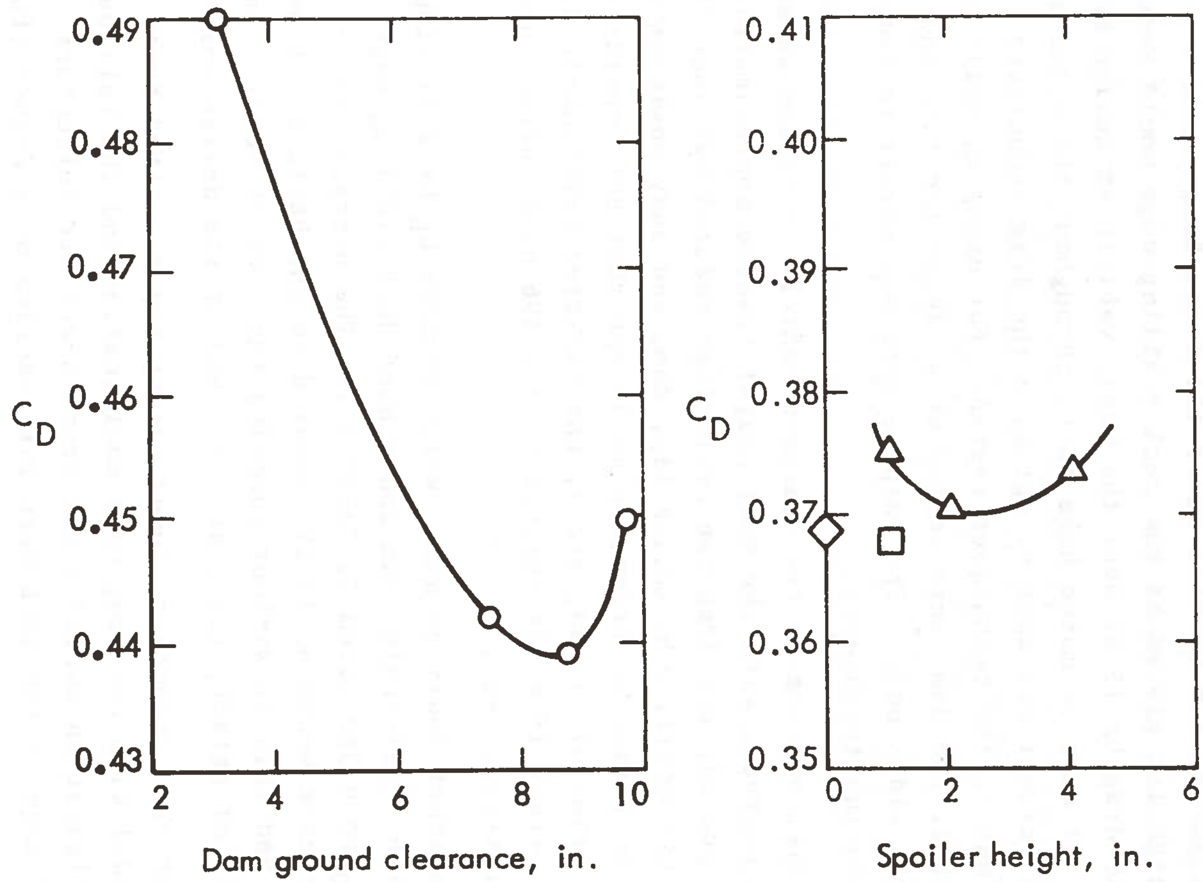

Figure 2-5. Dam and Spoiler Optimization Study on Mustang II Model in GALCIT 10-Foot Wind Tunnel

3. LOCKHEED-GEORGIA LOW-SPEED WIND-TUNNEL TESTS

3.1 INTRODUCTION

Three full-size vehicles were tested in the Lockheed-Georgia Low-Speed Wind Tunnel (LSWT 146) for the purpose of obtaining basic aerodynamic data in both unmodified and low-drag configurations. A total of 36 runs were made in 20 occupancy hours. Most of the test runs were made at a nominal free-stream velocity of 55 mph in the 16.25 x 23.25 foot test section. The corresponding dynamic pressure under standard day conditions is 7.75 pounds per square foot. The yaw runs were made through a yaw angle range of -3 to +15 degrees. Selected configurations were additionally tested at 30 and 100 mph but at 0 yaw angle only.

3.2 INSTALLATION

Airstream calibrations of the clear test section made during October 1974 showed that the airflow possessed 0.32-degree sidewash to the right over the region occupied by the vehicles. The local dynamic pressure distribution over this region was within ±0.4% of the mean. The clear test section static pressure coefficient gradient at a distance of 3 feet above the test section floor is -0.0008 per foot advance downstream.

The vehicles were mounted on the external balance by means of a four-point support system. The vehicles were not attached to the balance, but the wheels merely rested on the four pads, with transmissions in park gear and parking brakes locked. The friction between the tires and the pads was sufficient to maintain model position.

A standard installation procedure was adopted in order to minimize errors due to movement of the vehicle relative to the balance calibration center. The vehicle was installed reasonably symmetrically on the pads and a shake-down run made at the test wind velocity. The vehicle lateral, longitudinal, and yaw attitude was measured by suspending plumb bobs from the vehicle front, rear, and side midpoints relative to the test section reference centerlines. The side midpoint is defined as the mid-wheelbase point. The model was yawed as necessary for alignment with the airflow. Before making a wind-on data run, a weight-moment tare run was made over the test yaw angle range for subsequent use in the data reduction procedure.

The vehicle support system pads were instrumented with an array of surface pressure taps which were manifolded to a single pressure transducer for each pad. The pressure data gathered from these transducers were used to compute individual pad tare normal forces for correcting lift, pitching moment, and rolling moment data.

3.3 MODELS

The three cars tested were:

(1) 1975 Chevrolet Impala four-door sport sedan
(2) 1975 Plymouth Valiant four-door sedan
(3) 1974 Ford Mustang II two-door notchback coupe

Dimensional data for each car are given in Table 3-1 and an explanation of the symbols used to identify the various configurations tested is given in the Nomenclature section. Figures 3-1 through 3-8 show photographs of some of the car configurations tested. The basic cars were standard off-the-lot showroom floor models. Modification of the external shape in areas of significance to aerodynamic drag was effected by the use of sheet metal, cardboard, shaped styrofoam blocks, and adhesive cloth tape.

During this test, the suspension systems of all cars tested remained in the normal road condition, so the body was free to move on the chassis in response to the aerodynamic forces imposed in the wind tunnel. Measurements of ground clearance to fixed points on the car bodies, taken by means of scales mounted immediately behind a front and a rear wheel during and prior to a run, revealed a nose-up change in body attitude of only 0.03 degree on the Impala at 55 mph relative to zero speed. An analysis of the change in attitude of the Mustang II during the GALCIT test using actual spring rates coincidentally gave the same value of +0.03 degree. Changes of this magnitude can be neglected; however, during a 100-mph run, a change

TABLE 3-1. VEHICLE DIMENSIONAL DATA

Model	1975 Impala 4-dr. sport sedan	1975 Valiant 4-dr. sedan	1974 Mustang II notchback
Wheelbase, ft	10.13	9.25	8.02
Front track, ft	5.34	4.93	4.63
Rear track, ft	5.33	4.63	4.65
Frontal area, ft^2	25.3	21.7	19.36
Volume, ft^3	352.1	269.9	211.3
Overall length, ft	18.56	16.58	14.58
Overall width, ft	6.67	5.92	5.85
Overall height, ft	4.65	4.51	4.17

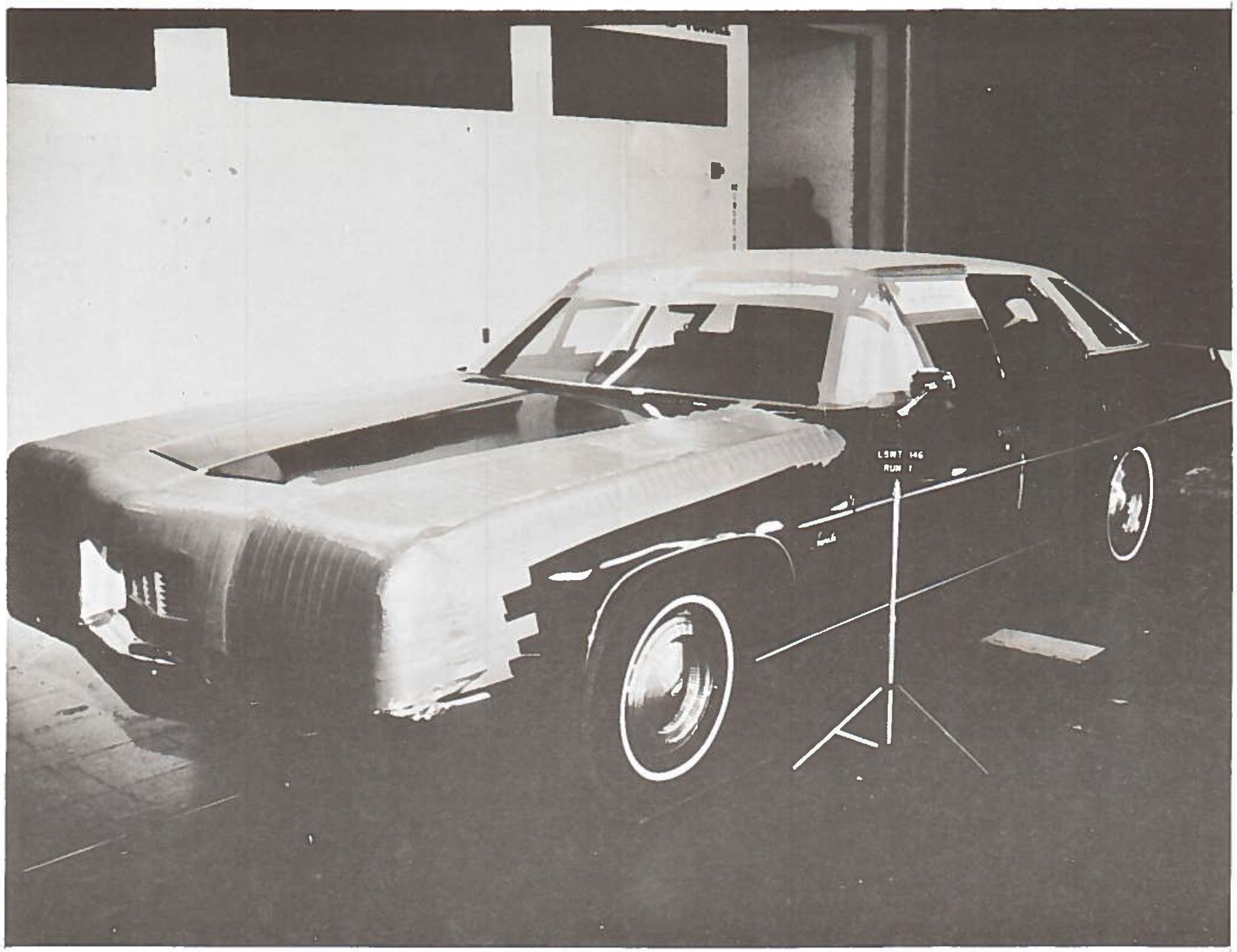

Figure 3-1. Front View of N2/P1/L/A1 Configuration on 1975 Impala in Lockheed Georgia Low-Speed Wind Tunnel

in attitude of 0.43 degree was measured on the Mustang II at Lockheed-Georgia. This indicates that the change in attitude is nonlinear with velocity as would be expected for an effect caused by aerodynamic forces.

During the Impala test, the body attitude was adjusted from 0.7 degree nose-up to 1.6 degrees nose-down by means of weights in the trunk or in the engine compartment. A plot of these runs and the normal attitude run gave an almost linear variation of C_D with angle α having a slope of $\Delta C_D/\alpha = 0.0094$/degree. In terms of $\Delta C_D/C_D$(STD), this amounts, for the standard Impala, to about 1.8% decrease in C_D per degree nose-down. The result is believed to be mainly due to increasing the slope of the hood and serves to demonstrate the sensitivity of drag to this sort of configurational change.

3.4 RESULTS

The results of this test are summarized in tables 3-2 and 3-3. In Table 3-2, the drag coefficient C_D and the other longitudinal coefficients, lift C_L and pitching moment C_m, are presented for various configurations tested. The configuration nomenclature is given in the Nomenclature section but can be briefly summarized as follows: N2 refers to a rounded nose, such as is shown in Figure 3-1; D3 and D9 are underbody dams (skirts) of various heights (Figure 3-2); P1 and P2 are smooth underpans entending from the front bumper to the rear axle and to the engine fire wall, respectively, with cutouts for the front suspension; L is a sharp 90-degree corner at the trunk deck-base intersection, as shown in Figure 3-3, and L1 is a 2-inch-high lip or spoiler mounted just forward of the trunk deck trailing edge radius, as shown in Figure 3-4; A is a window fairing, which approximates flush junctions of the windshield and side window upper edges as well as fairing around the A-post (see Figure 3-1). The same general designs were used on all cars, with modifications as required to fit. A dash (-) indicates standard configuration in the item region so indicated. In the case of the Impala, some of the modifications used in the wind tunnel test were also used to produce the N2/D3/L- configuration, which is the reduced-drag configuration, which is the reduced-drag configuration tested in the field.

TABLE 3-2. SUMMARY OF LOCKHEED-GEORGIA LOW-SPEED WIND-TUNNEL TEST RESULTS FOR LONGITUDINAL COEFFICIENTS[a]

Item	Configuration	C_D	C_L	C_m	ΔC_D	$\Delta C_D/C_D$ (STD), %	Remarks	Compare with item
				IMPALA				
1	Standard	0.511	0.608	0.168	-0-	-0-		
2	-/-/L/-	0.481	0.431	0.236	0.030	5.9		
3	N2/-/L/-	0.446	0.423	0.246	0.065	12.7	N2 = 6.8%	2
4	N2/D3/L/-	0.395	0.367	0.185	0.116	22.6	D3 = 9.9% (with N2)	3
5	N2/P2/L/-	0.427	0.404	0.269	0.084	16.5	P2 = 3.7% (with N2)	3
6	N2/P1/L/-	0.411	0.382	0.257	0.099	19.5	P2 = 85% of P1	5
7	N2/P1/L/A	0.402	0.395	0.248	0.109	21.3	A = 1.8% [illegible] $\psi = 0^\circ$	6
8	-/D3/L1/-	0.470	0.330	0.295	0.041	8.1		
9	N2/D3/L1/-	0.416	0.257	0.253	0.095	18.5	N2 = 10.4%	8
10	N2/P1/L1/A	0.427	0.296	0.306	0.084	16.5		
11	N2/P1/-/A	0.435	0.596	0.123	0.076	14.9	L1 = 1.6%	10
12	N2 + D3 + L				0.138	27.0	By addition of effects	4
				VALIANT				
13	Standard	0.565	0.632	0.122	-0-	-0-		
14	-/D3/L	0.498	0.471	0.177	0.066	11.8		
15	N2/D3/L	0.449	0.405	0.144	0.116	20.5	N2 = 8.7% (with D3)	14
16	N2/P2/L	0.473	0.368	0.113	0.092	16.3	D3 < P2 by 4.2%	15
17	N2/P2/L1	0.498	0.347	0.131	0.067	11.9	L < L1 by 4.4%	16
				MUSTANG II				
18	Standard	0.532	0.532	0.136	-0-	-0-		
19	-/-/L1	0.506	0.401	0.183	0.028	5.3		
20	-/D9/-	0.497	0.476	0.085	0.034	6.5		
21	-/D9/L1	0.477	0.353	0.140	0.055	10.3	D9 + L1 = 11.8%	19.20
22	N2/D9/L1	0.437	0.319	0.125	0.095	17.9	N2 = 7.5%	21
23	N2/-/L	0.478	0.469	0.160	0.054	10.2		
24	N2/D9/L	0.440	0.393	0.084	0.092	17.3	D9 = 7.1%, L1 < L by 0.6%	23.22
25	N2/P2/L	0.459	0.465	0.167	0.072	13.6	P2 = 3.4%	23

[a]The relative drag levels of the cars tested in the Lockheed-Georgia wind tunnel must not be taken as typical of their manufacturer's products. Another choice of cars from the same three sources will give a different ordering and probably different levels of drag.

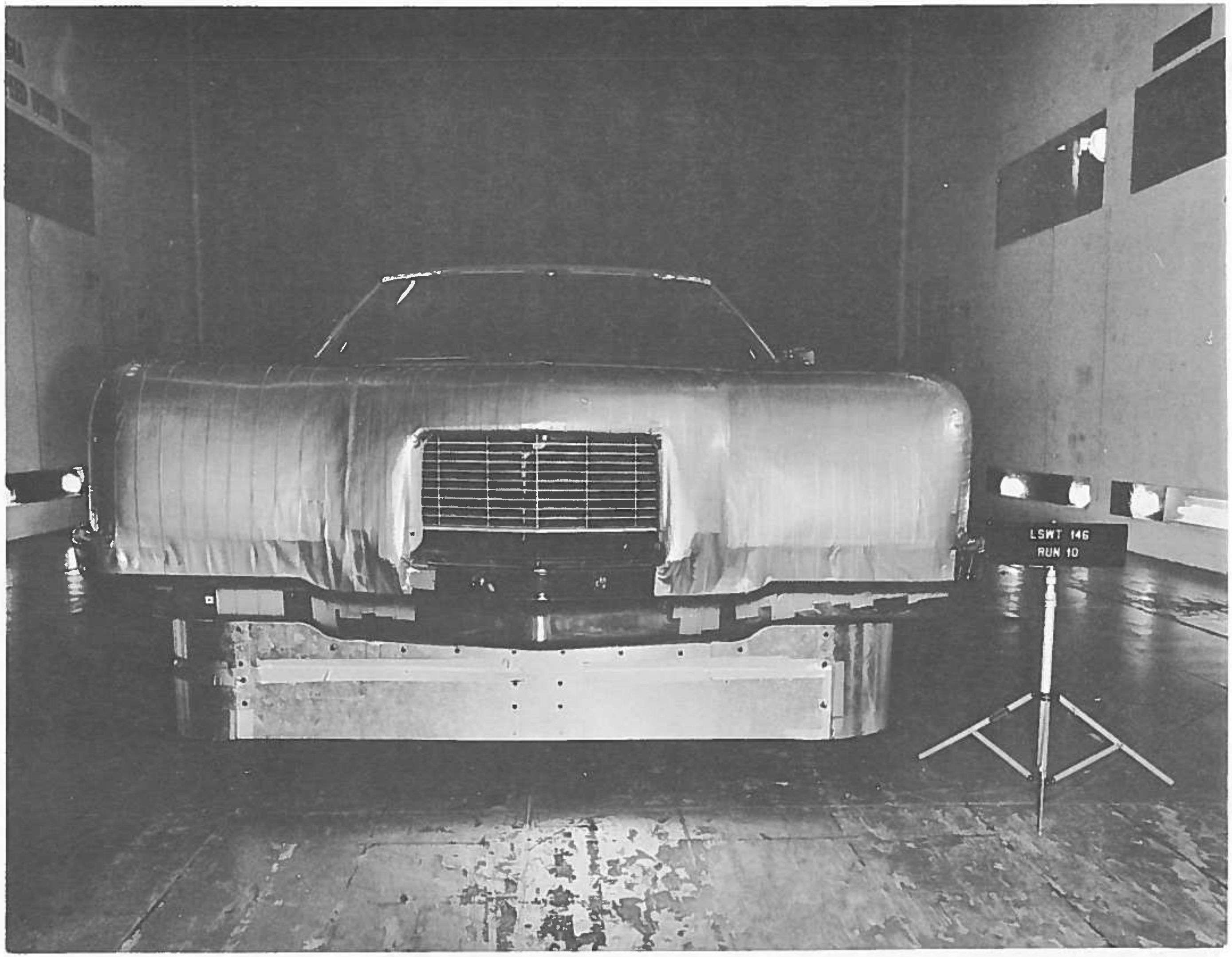

Figure 3-2. Front View of N2/D3/L/- Configuration on 1975 Impala in Lockheed-Georgia Low-Speed Wind Tunnel

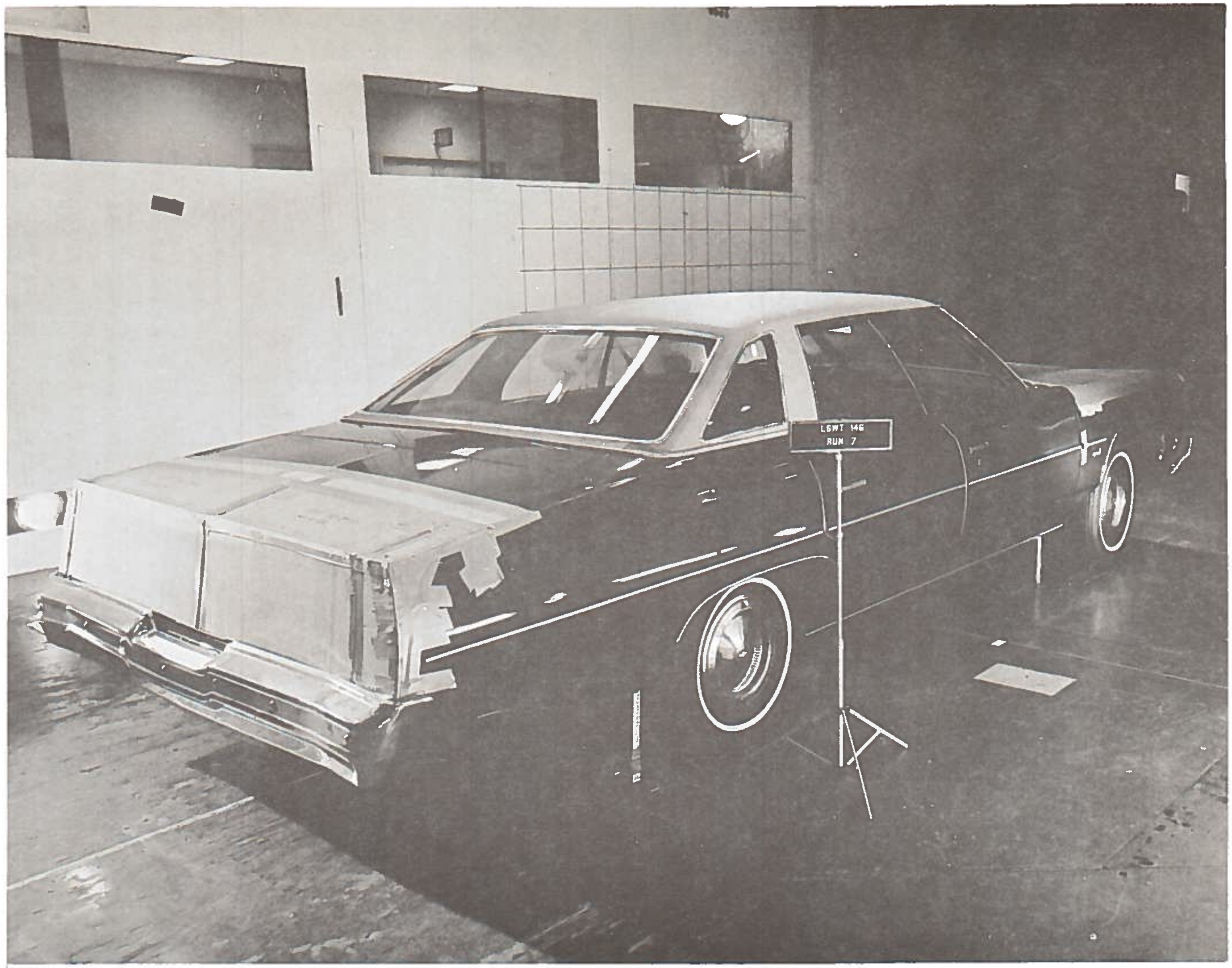

Figure 3-3. Rear View of N2/P1/L/- Configuration on 1975 Impala in Lockheed-Georgia Low-Speed Wind Tunnel

TABLE 3-3. SUMMARY OF LOCKHEED-GEORGIA LOW-SPEED WIND-TUNNEL TEST RESULTS FOR LATERAL COEFFICIENTS AT 12-DEGREE YAW

Configuration	C_Y	C_n	C_ℓ
IMPALA			
Standard	0.388	0.161	0.120
N2/P1/L/A1	0.406	0.123	0.105
N2/P1/L/-	0.427	0.123	0.111
N2/D3/L/-	0.397	0.091	0.101
-/D3/L/-	0.383	0.098	0.108
VALIANT			
Standard	0.564	0.136	0.149
N2/P2/L1	0.592	0.088	0.172[a]
N2/P2/L	0.642	0.100	0.180
N2/D3/L	0.553	0.073	0.148
MUSTANG II			
Standard	0.429	0.136	0.104
N2/P2/L	0.524	0.146	0.135
N2/D9/L1	0.539	0.120	0.145
-/D9/L1	0.507	0.113	0.128

[a]Interpolated value.

In general, the configurations are arranged in order of descending drag coefficient, although more than one series may be present, as in the case of the Mustang II. The columns headed ΔCD and $\Delta C_D/C_{D(STD)}$ in Table 3-2 are compared to the drag coefficient of the standard car[3] configuration. Comparisons between various modified configurations are noted in the "Remarks" column of the table. The data presented in this report have been corrected for the following wind tunnel interference effects: solid and wake blockage, horizontal buoyancy, and streamline curvature. The latter correction, which is not universally used on automotive wind tunnel test results, was applied according to the method devised by W.H. Bettes and K.B. Kelly in the GALCIT 10-foot wind tunnel. The effect of the streamline curvature correction is to reduce the drag coefficients of the standard configuration cars by 7.1% for the Impala to 5.8% for the Mustang II in the Lockheed-Georgia test, and by 6.2% for the Mustang II model in the GALCIT test. In keeping with standard automotive test practice in this wind tunnel, no corrections were made to the data for the nonrotating wheels, the nonscale zero relative velocity between vehicle and ground, or for the presence of an 8-10 inch boundary layer on the tunnel floor. In relative scale, this boundary layer is much thicker than the one in the GALCIT 10-foot wind tunnel because of the use of a ground board in that facility.

During each data run, a minimum of three data points were recorded at 0 yaw angle. Comparison of these data indicates the wind-on repeatability of force and moment loads arising from balance repeatability, airstream velocity, and angularity deviations, and from the effects of unsteadiness and hysteresis of the airflow associated with each vehicle. Pitching and rolling moment repeatability is further compounded by deflections. The average values provided by the analysis are shown in Table 3-4.

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[3] In the case of the standard car and all other configurations that included an unmodified nose, a dummy front license plate was mounted in the position provided by the manufacturer. For the modified nose, N2, no license plate was mounted.

TABLE 3-4. LOAD REPEATABILITY OF AERODYNAMIC COMPONENTS IN LOCKHEED-GEORGIA LOW-SPEED WIND TUNNEL

Component	Load repeatability	Coefficient equivalent at 55 mph
Lift	±1.07 lb	±0.0064
Drag	±0.54 lb	±0.0032
Pitching moment	±5.95 ft-lb	±0.0040
Side force	±0.76 lb	±0.0045
Rolling moment	±5.07 ft-lb	±0.0033
Yawing moment	±1.57 ft-lb	±0.0010

The most extensive series of configurations tested were on the 1975 Chevrolet Impala four-door sport sedan (hardtop), since this was to be the vehicle used for road testing. Much of the information in the table is self-evident, but some is not, and some additional comments seem warranted. The greatest drag reduction was obtained with the N2/D3/L/- configuration shown in Figure 3-2, even though the window fairing, which was worth an additional 1.8% (at ψ = 0 degree), was not used. The front dam, D3, was more effective than the underpan, P1. The underpan extending aft to the firewall was 85% as effective as the underpan configuration extending to the vicinity of the rear axle. In both cases, some additional improvement to the effect of the underpan could have been obtained if deflectors had been fitted in front of the front suspension members (lower A-arms), as was done on the Mustang II model in the GALCIT test. Item 12 in Table 3-2 shows that the individual effects of N2, D3, and L, obtained as differences between various configurations, are less than directly additive, since the 27% reduction obtained in this manner is greater than the 22.6% reduction obtained by direct measurement of the configuration. For simplicity, the data in Table 3-2 are all presented at zero yaw, but the effects on the drag reductions obtainable with the devices tested at reasonable angles of yaw must be considered. Because of the time required, not all configurations were tested through a yaw range, since the information obtained at zero yaw was considered to be indicative of the relative merits of the various devices tested. Figure 3-9 is a typical example of yaw effects on the longitudinal coefficients. Here it can be seen that the improvements obtained at zero yaw hold over the yaw range tested, although the magnitude of a decrease in C_D is somewhat reduced (to about 76% at ψ = 15 degrees for C_D, in this case for the N2/D3/L configuration). The only exception to the decrease in effectiveness at yaw among the modifications tested was the window fairing (A), where an effect in $\Delta C_D/C_{D(STD)}$ of 1.8% at ψ = 0 degree increased to 3.2% at ψ = 12 degrees. Data at angles of yaw greater than 15 degrees would have been of interest, since they can readily occur on the highway in some parts of the country due to higher wind levels, but the increase in blockage as the cars were yawed prevented the obtaining of reliable data at higher angles.

For the 1975 Valiant four-door sedan and for the 1974 Mustang II, results quite similar to those of the Impala were obtained, although fewer configurations were tested. For both cars, the front underbody dam was more effective than the underpan to the firewall. In the case of the Mustang II, a 2-inch-high spoiler at the rear trunk edge (L1) was approximately equal in effectiveness to the sharp corner configurations (L), while for the Valiant, the L-configuration was clearly superior, as it was for the Impala.

It is perhaps worth commenting here that test time did not permit the optimization of the devices tested as to location or geometry, with the limited exception of the Mustang II, where some work was done on the model in the GALCIT test to optimize dam height and spoiler height and location. These results were applied as best they could to the other cars used in the Lockheed-Georgia tests.

The effects of the modifications on the aerodynamic coefficients other than C_D must also be investigated to be certain that adverse handling conditions do not occur. The most noteworthy of these changes is the reduction in lift coefficient caused by the addition of a corner or spoiler to the trunk. The effect of the change is favorable, since it destroys some of the lift generated by the air-foil-like shape of the car body and increases the tractive forces between tires and road. That most of the lift is destroyed at the rear of the car is demonstrated by observing that the sizeable loss of lift between items 1 and 2 in Table 3-2 is accompanied by a small increase (nose-up) in the pitching moment C_m about the center of gravity, but can be more clearly seen if the lift coefficient is broken into components at the front and rear axle. When this was done for items 1 and 2, the C_L on the rear axle changed from 0.136 to -0.035, while the front axle lift coefficient increased slightly from 0.471 to 0.486. Front axle lift was decreased when the front dam was added to the cars. Comparing item 4 to the standard configuration, item 1, the front lift coefficient decreased from 0.471 to 0.364, while the rear changed from 0.136 to 0.001. This is a side benefit to the use of front dams rather than underpans as drag reduction devices. The effect on front lift could probably be accentuated by designing the dam so that the front edge extended forward of the attachment point, but at the normal highway speeds of today, there is little problem with front end lift on most standard cars. For reasons of styling, the forward-extending design may be preferable, however. In Table 3-3, the lateral coefficients at 12 degrees yaw for those configurations where yaw data were taken are presented and summarize the lateral effects of the drag reduction devices. A typical set of curves for side force coefficient C_y, yawing moment coefficient C_n, and rolling moment coefficient C_l are shown in Figure 3-10. Since cars are aerodynamically unstable, a decrease in any of these coefficients relative to the value for the standard configuration is favorable. The side force coefficient was somewhat increased due to the addition of lateral area at both the nose and in the rear; in the former case, the addition of area is not real, since the rounded nose was, of necessity mounted forward of the standard nose but would not be on a production vehicle. (This test technique is often used in wind tunnel automotive testing as an expedient to avoid extensive modifications to either a model or full-scale vehicle.) Even so, this slight adverse effect would not be expected to cause handling qualities to seriously deteriorate, since both the rolling moment coefficient and the yawing moment coefficient are favorably affected in most cases by the modifications.

3.5 COMPARISONS WITH SUBSCALE TEST

Table 3-5 presents comparisons of Mustang II configurations tested in both the model and full-scale wind tunnel tests. It is evident that values of drag coefficients obtained on the model at GALCIT are significantly lower than those obtained on a prototype vehicle at Lockheed-Georgia. (The column headed ΔC_D is $\{[C_{D(L-G)} - C_{D(GALCIT)}]/C_{D(L-G)}\}$. The increased values of $\Delta C_D\%$ for configurations with the modified nose, N2, are believed due to slight differences between the model and prototype N2 noses. The production car should be expected to have a drag coefficient significantly greater than the model because of several factors, such as the free suspension of the car (the model height and attitude were held fixed) and the aerodynamic life and pitching moment acting. Assuming the vehicle traveling at 55 mph, carrying only the driver, with no load

TABLE 3-5. COMPARISONS OF LONGITUDINAL COEFFICIENTS OBTAINED DURING SUBSCALE AND FULL-SCALE WIND-TUNNEL TEST (MUSTANG II)

Configuration	L-G C_D	GALCIT C_D	ΔC_D, %	L-G C_L	GALCIT C_L	L-G C_m	GALCIT C_m	L-G $\delta C_D/C_{D(STD)}$, %	GALCIT $\delta C_D/C_{D(STD)}$, %
Standard	0.532	0.469	11.8	0.532	0.503	0.136	0.144	-0-	-0-
-/D9/-	0.497	0.438	11.9	0.476	0.479	0.085	0.091	6.5	6.6
N2/D9/L1	0.437	0.382	12.6	0.319	0.310	0.125	0.155	17.9	18.6
N2/D9/L	0.440	0.380	13.6	0.393	0.376	0.084	0.132	17.3	19.0

$\Delta C_D = C_{D_{L-G}} - C_{D_{GALCIT}}$

$\delta C_D = C_D - C_{D_{STANDARD}}$

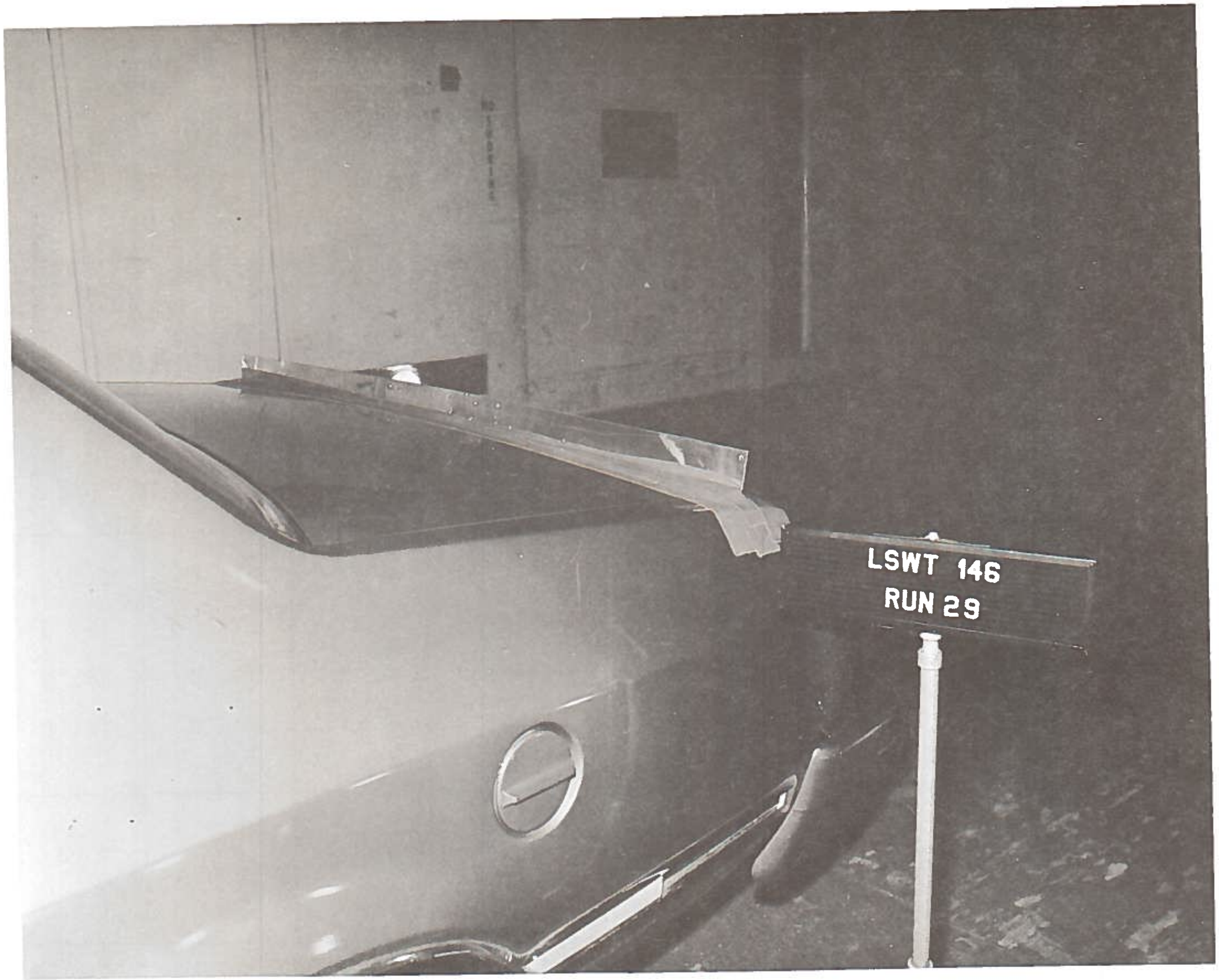


Figure 3-4. L1 Spoiler on Trunk of 1974 Mustang II in Lockheed-Georgia Low-Speed Wind Tunnel

Figure 3-5. Front View of N2/P2/L Configuration on 1974 Mustang II in Lockheed-Georgia Low-Speed Wind Tunnel

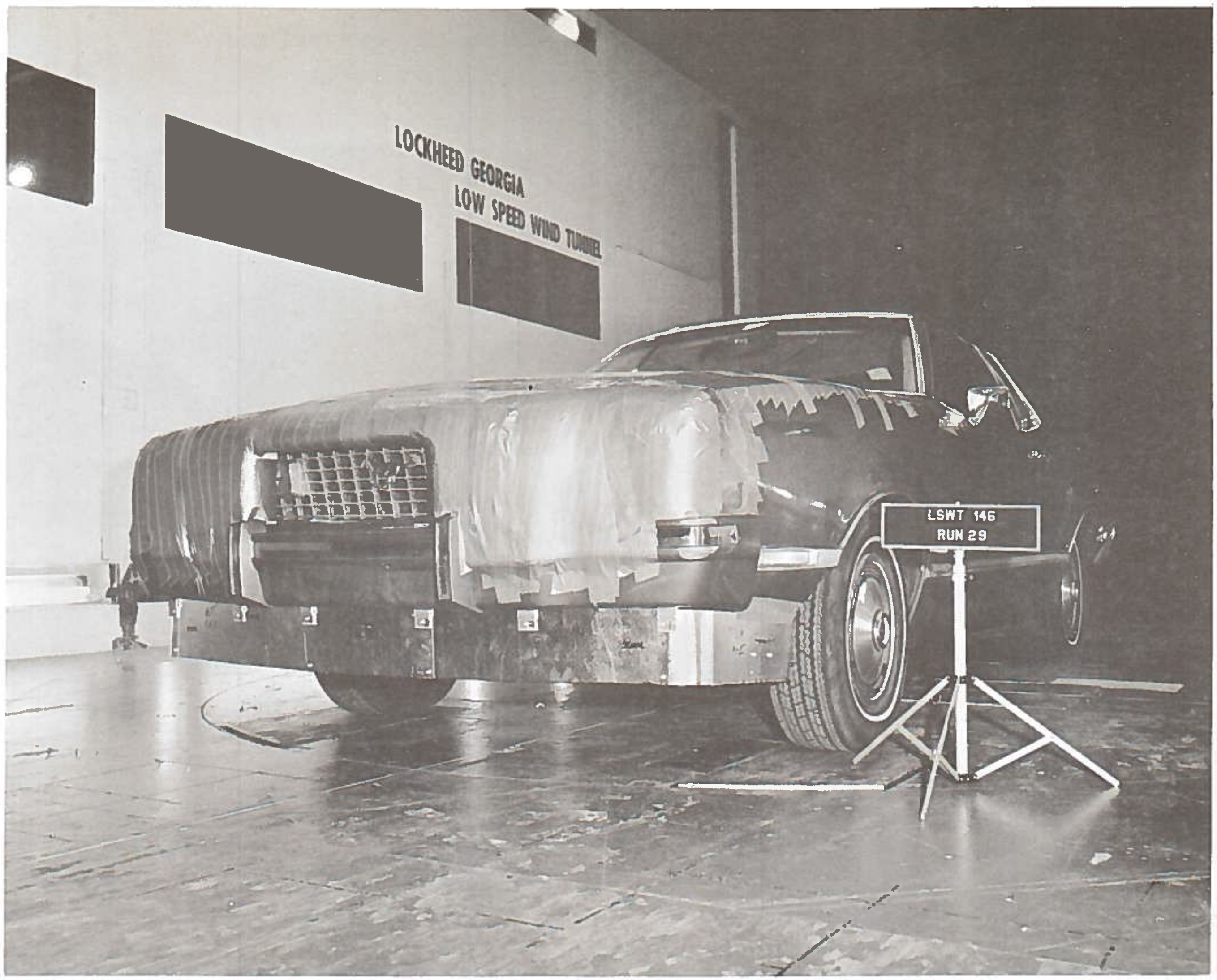


Figure 3-6. Front View of N2/D9/L1 Configuration on 1974 Mustang II in Lockheed-Georgia Low-Speed Wind Tunnel

Figure 3-7. Rear View of N2/P2/L Configuration on 1975 Valiant in Lockheed-Georgia Low-Speed Wind Tunnel

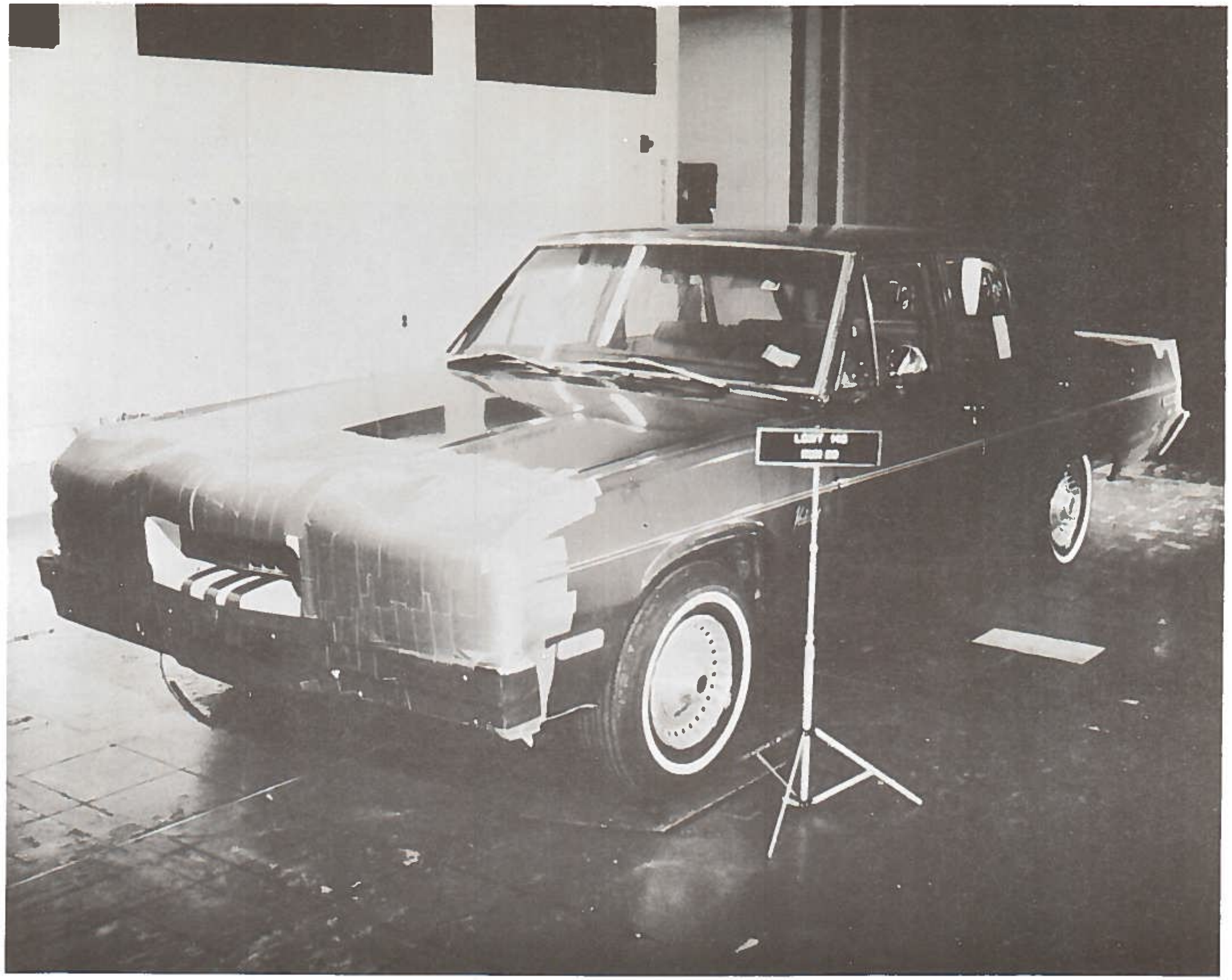


Figure 3-8. Front View of N2/P2/L Configuration on 1975 Valiant in Lockheed-Georgia Low-Speed Wind Tunnel

in the trunk, and a front end spring rate of 260 lb/in. and a rear end spring rate of 90 lb/in., the vehicle height above the road would be increased by 0.19 inch and the body angle of attack would be 0.03 degree using the force and moment coefficients acquired during the test on the standard configuration. Additional weight in the vehicle would tend to increase the angle of attack further. Data acquired during the model test where the effects of body angle of attack and height were investigated indicate that the drag coefficient would be increased by a minimum of 0.0012 due to the increase in body attitude and height at 55 mph. Other factors include body detail omitted from the model, production gaps at sheet metal joints, and air leaks between cabin interior and exterior which can, as previously mentioned, add between 5 and 8% to the drag coefficient and result in a C_D = 0.51. (The degree of body detail present in the model can be judged from Figure 2-1 and 2-3.) The drag coefficient for the production vehicle traveling at 55 mph would thus be expected to be no less than 0.51. The 4% difference which still remains can tentatively be assigned to the small geometric differences between the 0.4-scale model and the production model and to differences which exist between the two test facilities in such areas as boundary layer thickness in the test section, model-tunnel interference factors, etc. The drag coefficient might also be different if other shapes or other wind tunnels were involved. The available results from these tests are insufficient to go further with the comparison of absolute levels.

The reduction of drag relative to the drag of the standard configuration tested in the same facility is given in the second and third columns on the left in Table 3-5. Here the agreement is better, especially between the two configurations with the unmodified noses. The larger deviations for the configurations with the modified noses may be due to small differences in nose contours between the model and the prototype. These columns serve to illustrate that subscale wind tunnel tests can be made to serve a useful function in the aerodynamic design process. Automobile models, although expensive to construct, can be built sufficiently early in the design cycle

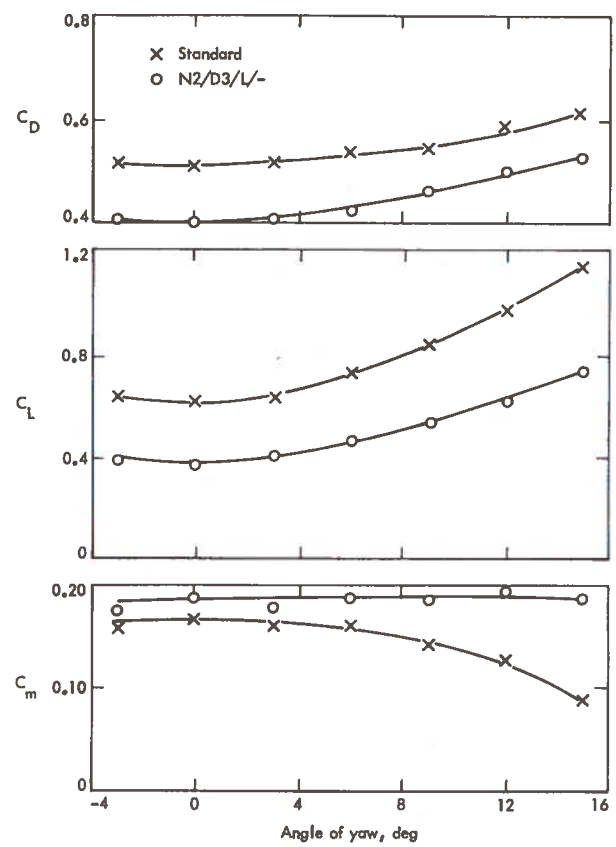


Figure 3-9. Effect of Yaw Angle on the Longitudinal Coefficients of the Impala in the Standard and N2/D3/L/- Configurations

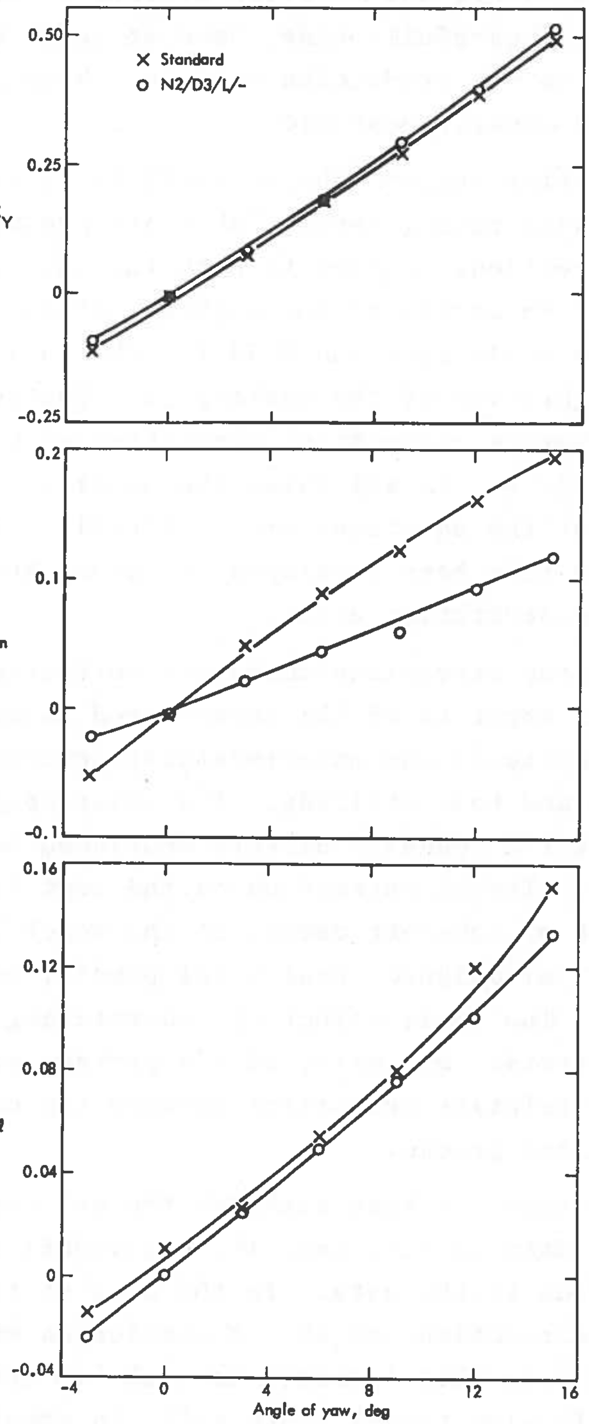


Figure 3-10. Effect of Yaw Angle on the Lateral Coefficients of the Impala in the Standard and N2/D3/L - Configurations

so that the results, i.e., the relative effects of various changes, which are reliable if carefully done, have at least a chance of being incorporated in the production vehicle. With prototype tests alone, this is not usually possible.

In order to better suggest the reliability of comparisons between these two wind tunnel tests, Table 3-6 presents the details of the various corrections applied to both the sub-scale and full-scale data in order to arrive at the highway values of C_D equal to 0.51 for the sub-scale test and 0.53 for the full-scale test on the standard configuration of the Mustang II. Bouyancy, blockage, and streamline curvature corrections were obtained by means of the equations in Appendix A. In all cases the model and tunnel dimensions were such that the equations are applicable. Although empirical in nature, they have been developed for blunt bodies where large areas of flow separation exist.

In both tests the streamline curvature correction is the largest of the three and is about 6% of the uncorrected values. The next line of the table contains the experimentally-determined correction for road clearence and body attitude. Its value could be slightly effected by some of the boundary effects mentioned below, and the loading of the car. The 8% correction on the next line includes the effects of lack of complete detail on the model body and underbody, missing gaps, misaligned sheet metal panels, and differences in internal flows. The small effect of non-rotating wheels is neglected in both tests. So, also, is the perhaps more important effect of improper relative velocities between the car underbodies, the air stream and the ground.

A point to be noted is that although the net correction to the sub-scale test data is less than 1%, individual corrections of +8% and -6% were made to the data. In the case of the full-scale data, the largest correction was 6%. A conclusion which can be drawn from Table 3-6 is that it would be risky to conclude that sub-scale and full-scale wind tunnel tests will, in general, give results which compare as favorably as do those of this single-point comparison.

TABLE 3-6. DEVELOPMENT OF ROAD-AERODYNAMIC DRAG COEFFICIENT DATA FROM SUB-SCALE AND FULL-SCALE WIND-TUNNEL TEST RESULTS

Sub-Scale Test		Full-Scale Test		Comments
C_D or ΔC_D	%	C_D or ΔC_D	%	
.5054		.5818		Uncorrected values of C_D
.0083	1.6	-.0005	-0.1	Horizontal bouyancy
-.0135	-2.7	-.0149	-2.6	Solid and wake blockage
-.0308	-6.1	-.0346	-5.9	Streamline curvature correction
.0012	0.2	-0-	-0-	Model ground clearence and attitude
.0404	8.0	-0-	-0-	Body detail and sheet metal, etc.
---		---		Non-rotating wheels
---		---		Improper underbody/ground relative velocity
------	-----	--------------		
.5110	0.9	.5318	-9.4	

4. FIELD TESTS

4.1 INTRODUCTION

The field test portion of this program was conducted to obtain aerodynamic drag coefficient values for comparison with the results of wind tunnel tests performed earlier. The method chosen for the field tests was the coast-down technique. This technique permits data to be obtained at any desired velocity range and in both directions on the test roadway. The vehicle was accelerated to some velocity on a level roadway and allowed to coast through an instrumented section of roadway while the required data were recorded. These data, in conjunction with other information about the vehicle, the roadway, and the atmospheric conditions, were then processed in the data reduction program to determine the aerodynamic drag coefficient as well as the rolling resistance of the vehicle. Once the rolling resistance characteristics were known, the variation in drag coefficient due to add-on devices could be accurately determined.

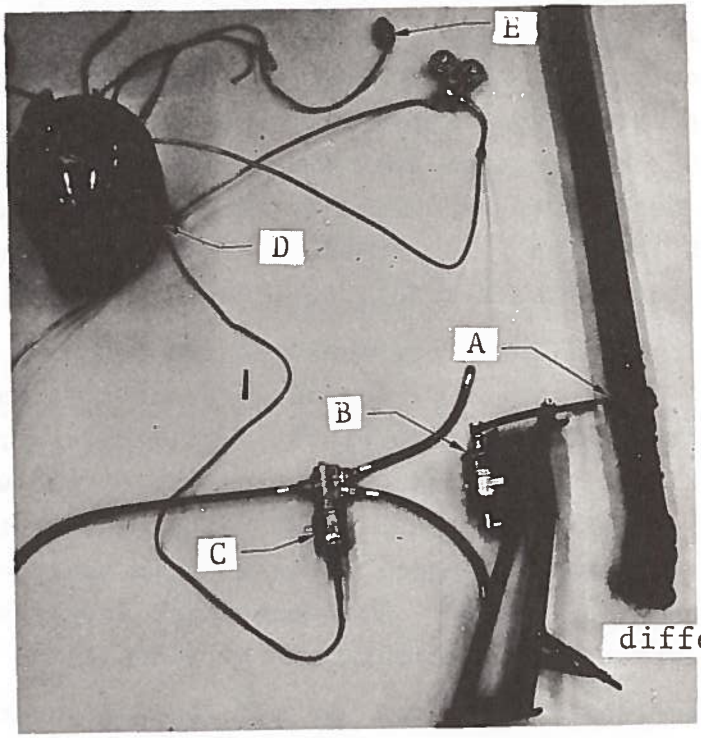
4.2 TEST DESCRIPTION

A test of this type demands that careful attention be paid to the design of the experiment. The variables that would affect the data were defined, and an assessment was made as to whether these variables could be controlled or only measured. The results of the definition and assessment process indicated that (1) for the vehicle, the rolling resistance should be minimized and the characteristics known for data reduction pruposes; (2) for the roadway, a test section must be chosen that has a minimal grade change and is of a consistent surface texture; and (3) for the atmospheric conditions, no control was possible, but limiting conditions for testing were established and test conditions were recorded.

The vehicle used for the coast-down testing was a 1975 Chevrolet Impala sport sedan, the same model that was tested in the full-scale wind tunnel portion of this program. The Impala is manufactured with an automatic transmission as standard equipment, and since this type of transmission has high internal drag even in the neutral position, a means of uncoupling the transmission from the drive wheels was devised. A special drive shaft was constructed such that the driver could, by turning a switch, activate a pneumatic system that decoupled the forward part of the drive shaft from the rear part and allowed the two parts to rotate independently. (This system is shown in Figure 4-1.) Thus only the friction of the differential and rear axle contributed to the rolling resistance of the drive train.

The rear brakes were of the conventional drum type which do not contribute significantly to rolling resistance, never the less, the "automatic" adjustment feature was made operative and the brake-shoes backed off, but it was determined that the front disc brakes could affect the rolling resistance by virtue of the fact that the brake pads in disc brakes are in contact with the disc itself even when the brakes are not being applied. To eliminate the possible effect of the front brakes dragging, the housings containing the pads were removed and banded to the upper A-arms on the front suspension. With these two uncertainties removed from the system, the only remaining factors that could influence the data were the tires and the operating conditions of the vehicle.

Firestone Tire and Rubber Company's Central Research Laboratories furnished a set of H78-15 4-ply polyester bias tires that were specially prepared for these tests. Firestone measured the rolling resistance of the tires in the speed range from 20 to 60 mph at two load values (1000 and 1500 pounds) and at three tire inflation pressures. The tires were first tested with full treads; subsequently, the tread was carefully buffed off so that the tires were smooth. The buffed tires were then retested for the rolling resistance measurements. The results of these measurements were used as the tire rolling resistance for those test runs in which the buffed tire rolling resistance for those test runs in which the buffed tires were used. Runs were also made with the tires (Uniroyal PR-6 radials) that were supplied with the car. The tire temperatures and pressures were measured and recorded before and after each run. Tire pressure adjustments were made when necessary in order to maintain constant temperature and pressure values throughout the test series.



A - Decoupler spline
B - Pneumatic cylinder
C - Electric valve
D - Pressure supply tank
E - Control switch (located in steering wheel area)

Figure 4-1. Drive Shaft Decoupler System

The operating conditions that would affect the data were the temperature of the oil in the differential, the tire temperatures and pressures, and the weight of the vehicle. A pretest warm-up procedure was devised that would minimize the tire and differential effects. Prior to any testing, the vehicle was driven up and down the roadway in a zig-zag pattern to bring the tires to operating temperatures and pressures. Also, during this period, the vehicle was periodically accelerated harshly to bring the temperature of the oil in the differential up to a steady-state level, thus minimizing the variation of this effect from test run to test run. The weight of the vehicle was determined by carefully monitoring the fuel level in the car for each test run. Adjustments were then made to the measured weight of the car with a full fuel tank.

The atmospheric conditions were measured and recorded for each test run. The wind velocity and direction were known to have the greatest effect on the data and, therefore, test limits were determined for these variables. No test runs were made if the wind velocity parallel to the test roadway was greater than 100 feet per minute or when the average yaw angle of the vehicle would exceed 3 degrees during a run. The ambient air temperature and pressure were recorded for the purpose of determining the air density.

A survey of available test sites was made and an inactive runway at Edwards Air Force Base, California, was selected. The runway is known as the Barrier Facility runway. A 7100-foot section of this 9220-foot paved runway was replaced in 1973 and surveyed in 1974 by the US Army. A 5000-foot section of the newly constructed part of the runway was selected for use. The section selected has a minimum amount of grade changes and yet allows the vehicle to be accelerated to the required velocities; it also allows for a safe stopping distance without the car leaving the paved area. The average grade slope for the test section was 0.002.[4] The surface roughness of the concrete runway was equivalent to that of a new freeway surface. All expansion joints were filled and were not noticeable when driven over. Figure 4-2 is a view of the runway test section.

[4] For data reduction purposes, the test section was divided into three sections of different grades for the precision required in the program.

The 5000-foot test section was instrumented with roadway contact switches every 500 feet. Figure 4-2 shows a switch installed on the test section. These switches were hard-wired to two electronic counters so that, as a switch was closed, one counter would stop and the other would start. The counters were in turn wired to a printer that was activated whenever either of the counters was stopped. Figure 4-3 shows these instruments in the instrument van. This system measured the time it took the vehicle to coast from one station to the next, i.e., the coast time for each 500-foot section. The time was recorded to the nearest millisecond. The power for the instrumentation was supplied by a portable generator through a voltage regulator.

Wind velocity measurements were made using an Alnor Velometer. This instrument has several velocity ranges; for this test, the lower range (0 to 300 fpm) was used. The wind angle was determined by observing the angle between the test roadway and streamers mounted at several locations along the edge of the roadway. The ambient air temperature and pressure were obtained hourly from the Air Force Weather Service at the base.

4.3 TEST PROCEDURE

A test procedure was devised to minimize the variation of test parameters between test runs. The car was prepared in the test configuration, and the drive shaft decoupler was checked for proper operation. The driver next performed the warm-up procedure described earlier. The car was then checked again, and the fuel tank was topped off. The wind velocity was checked, and when conditions were acceptable, the tire temperature and pressure were measured and recorded. The vehicle was accelerated to a velocity slightly above the desired test value, the decoupler was activated, and the gear selector lever was placed in the neutral position prior to the car entering the test section. The data were automatically recorded as the car coasted through the test section. During the coast-down, the driver took extreme care to keep the car in a straight line to prevent any loss in velocity due to the scrubbing of the front tires that occurs when the wheels are turned even slightly. After the test run, the tire conditions were again measured and recorded.

Figure 4-2. Roadway Surface with Switch Installed

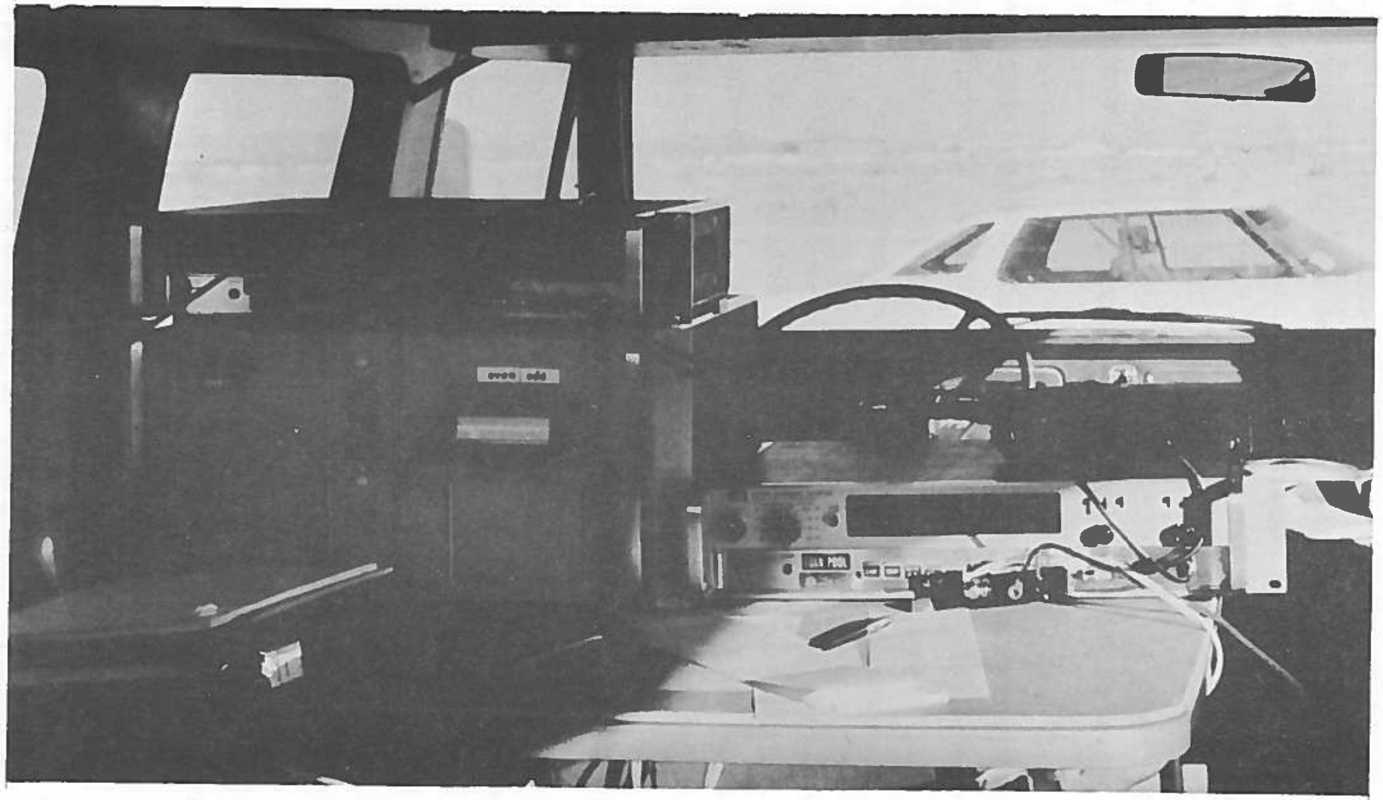


Figure 4-3. Internal View of Instrumentation Van

4.4 COMPLETED RUNS

A total of 48 runs were made between mid-January and mid-February 1975. The first 18 of these runs were made to check out the instrumentation and the data reduction techniques. The remaining 30 runs were divided into five groups of runs for five different car-tire combinations, as shown in Table 4-1. The standard and low-drag configurations were the same as those tested in the wind tunnel. Front and rear views of the low-drag configuration are shown in Figures 4-4 and 4-5, respectively.

The raw data and test conditions from these runs were checked on site to ensure that all were acceptable. Unacceptable runs were discarded and repeated. The runs listed in Table 4-1 are those that were acceptable for data reduction purposes.

In addition to these runs, 10 photo runs were made at different speeds. The photographs were used to determine the angle of attack of the car at the speeds tested. As in the wind tunnel tests, the angular deviations from the zero velocity conditions were negligible.

4.5 RESULTS

Each of the five configurations described earlier was run a minimum of six times (three in each direction on the roadway). The modified low drag car (N2/D3/L/-) exhibited a 22.4% drag reduction over its standard counterpart. Paradoxically, the drag was also reduced a few percent from the standard configuration with the front side windows open. Maximum RMS deviations resulting from best-fit curves through all these data averaged less than 0.05 second, which is considered to be indicative of excellent quality in the data. Table 4-2 summarizes the results of the road test.

The linear rolling resistance slope of the buffed Firestone tires at 28 psi was determined from Firestone calibration data to be 6.1×10^{-5}. The differential and wheel bearing resistances were experimentally determined to contain a linear speed-dependent term which could be superimposed on the tire rolling resistance slope, resulting in an effective linear rolling resistance slope, (C_{RN}) of 8.38×10^{-5}. With this value fixed in the data reduction,

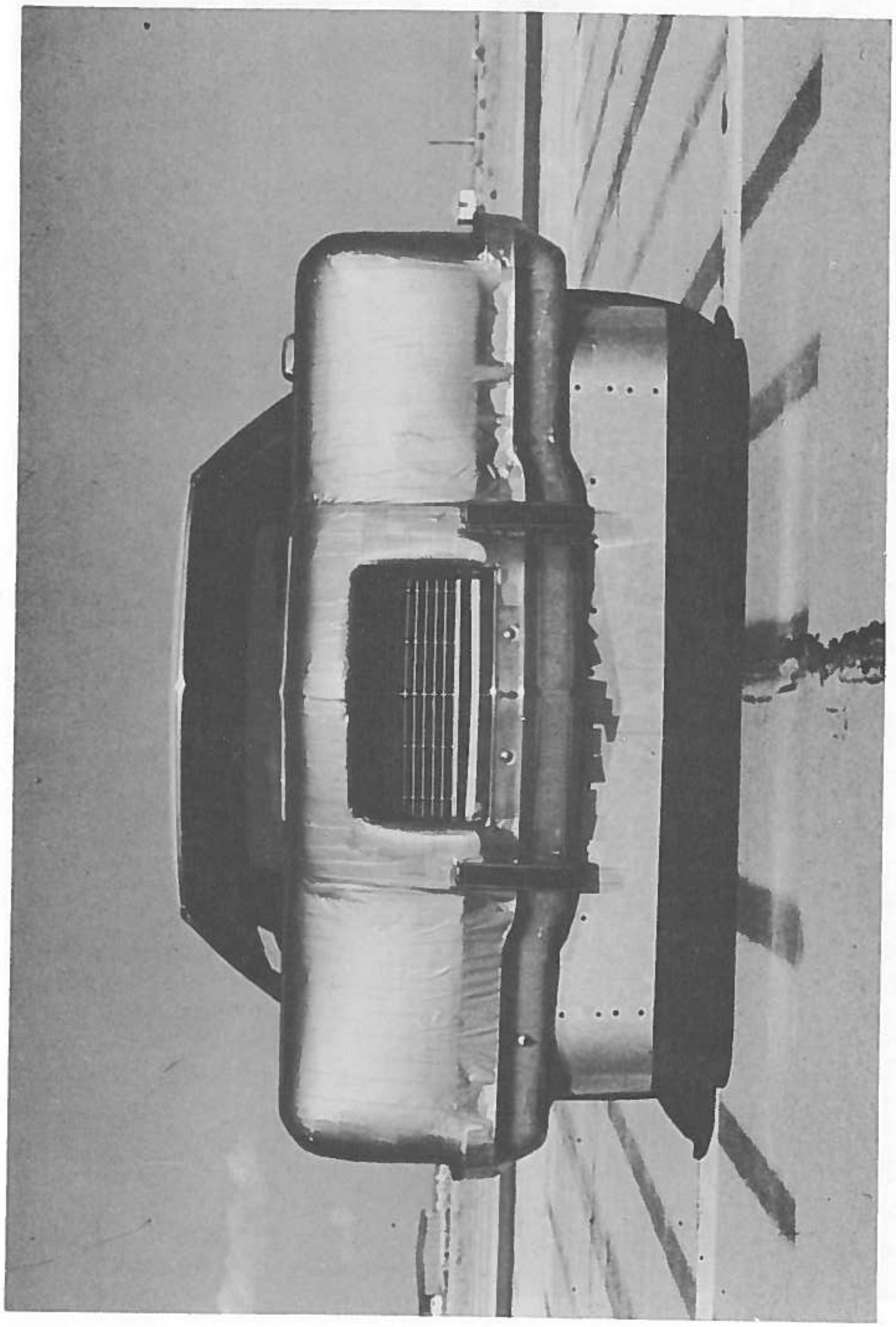


Figure 4-4. Front View of Low-Drag Configuration

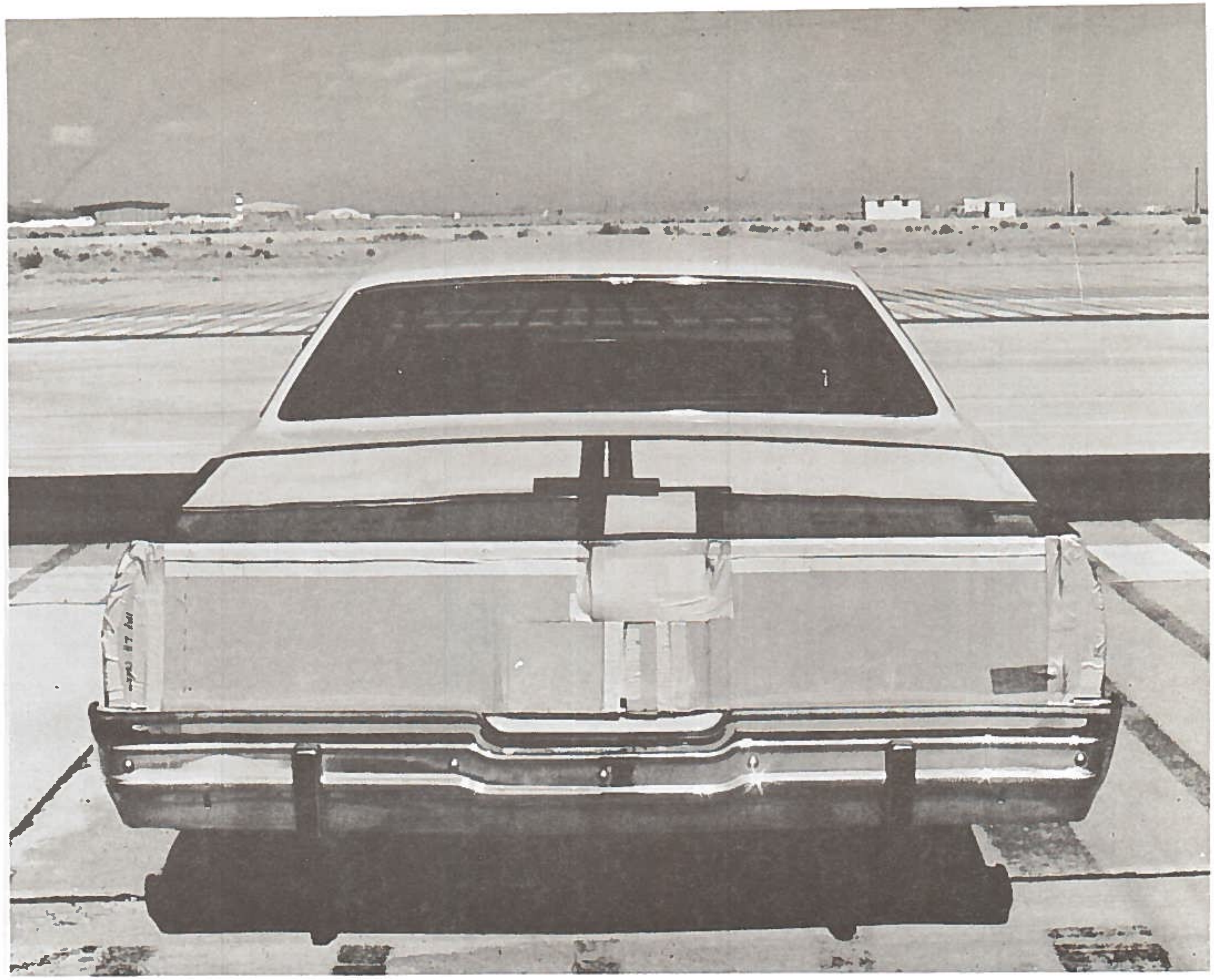


Figure 4-5. Rear View of Low-Drag Configuration

TABLE 4-1. CONFIGURATIONS AND NUMBERS OF RUNS MADE DURING ROAD TESTS

Group	No. of runs	Configuration	Tires	Tire pressure, psig
1	8	Stock	Buffed	28
2	6	Stock	Buffed	47
3	4	Front windows down	Buffed	50
4	6	Stock	Radials	34
5	6	Low-drag (N2/D3/L/-)	Buffed	49

TABLE 4-2. SUMMARY OF RESULTS FROM ROAD TESTS

Car configuration	Tire	Tire press./temp.	$\bar{C}_D$	$\bar{C}_R$	$\bar{C}_{RN}$[a]
Standard	Firestone buffed	28/75-80	0.509	0.0123	[8.38×10^{-5}]
Standard	Firestone buffed	50/65	0.505	0.0093	[8.18×10^{-5}]
Standard (Front windows down)	Firestone buffed	50/85	0.492	0.0082	[8.18×10^{-5}]
Standard	Uniroyal radial	35/95	[0.505]	0.0093	[9.36×10^{-5}]
Low-drag (N2/D3/L/-)	Firestone buffed	50/75-85	0.392	0.0087	[8.18×10^{-5}]

[a]Includes a term due to the measured resistance of the differential and wheel bearings,

Note: Brackets denote values which were fixed in the data reduction, as explained in section B. Bars over symbols indicate mean values.

the standard car drag coefficient was found to be 0.509. The standard car was re-run with the same buffed tires at 50 psi. Using a second Firestone calibration at this pressure, the drag coefficient was found to be virtually unchanged as expected. This agreement would be even better if C_{RN} were modified to reflect the difference in tire temperatures.

Because of the unexpected results with the front windows open, these data were subjected to more than normal scrutiny. Absolutely no basis could be found by which to discount these data. However, before any conclusions should be reached, additional comparative runs must be made.

The standard car drag coefficient was held fixed at 0.505 in order to calculate the linear rolling resistance slope of the Uniroyal radial tires at 35 psi. This was determined to be about 14% greater than the buffed 50 psi test tire. Fixing the rolling resistance slope of latter, the low-drag car was found to have a drag coefficient of 0.392 which amounts to a 22.4% reduction.

The linear intercept C_R is not the rolling resistance coefficient at zero velocity but only an extrapolation of the linear slope to that point. It is a function of the tire, the pressure, and the operating temperature. An equilibrium tire temperature increase from 65 to 85° (the difference was due to ambient roadway temperature) resulted in a 13% decrease in the effective rolling resistance at 50 psi for the buffed Firestone tires; reducing the pressure to 28 psi increased the effective rolling resistance by over 30%.

Some statistical analysis was performed in order to determine the consistency and quality of the data. The mean value of the drag coefficient is known to within ±1%, with a confidence level of 90% for the standard car and 54% for the low-drag car (85% confidence level to within ±2%). The reason for the difference in accuracies is not clear. Possible causes could be a slightly greater variation in equilibrium tire temperatures or flucturation in wind velocity and direction during this run set.

A more direct appreciation of the validity of the results from coast-down testing can be obtained by making comparisons of the reduced data obtained using the buffed Firestone tires. As was already mentioned, the change in inflation pressure (28 vs 50 psig) affected the inferred C_D by less than 1%, even though the rolling resistance was changed by some 25%. This virtually-zero change in C_D substantiates the testing techniques.

Another indication of the validity of the testing techniques is given by the comparison of the tire $\overline{C}_R$ values at the 50 psig inflation pressure for the various car configurations (standard, front windows open, low-drag). Although the values of $\overline{C}_R$ are not identical, this can be accounted for by the large variations in ambient temperatures. The observed variation of $\overline{C}_R$ with tire wall temperature is internally consistent and is as would be expected.[5]

Direct comparisons of the drag coefficients obtained from the full-scale wind tunnel and coast-down tests for the standard and the low-drag (N2/D3/L/-) configurations of the Impala are given in Table 4-3. The corrections applied to the wind tunnel drag coefficients are shown in Table 3-5 and discussed in the accompanying text. No equivalent corrections were applied to the drag coefficients obtained from the reduction of the coastdown data since actual road boundary conditions are inherent in the test technique.

Direct comparisons of the drag coefficients obtained from the full-scale wind tunnel and the coast-down tests for the standard and the low-drag (N2/D3/L/-) configurations of the Impala are given in Table 4-3.

The agreement in both cases falls well within the scatter band of both data sets and therefore must be considered not significant at the level indicated in the table. Clearly, however, the agreement between the two testing techniques is excellent in these two cases.

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[5] W.W. Curtiss, "Low Power Loss Tires," SAE Paper 690108, Jan. 1969.

TABLE 4-3. COMPARISONS OF ROAD TEST AND FULL-SCALE WIND-TUNNEL TEST RESULTS

Standard	0.508	0.511
Low-Drag(N2/D3/L/-	0.390	0.395

It is very important to emphasize, at this point, that the generalization that the two techniques will give good agreement over the range of shapes of motor vehicles should not be made even for the particular wind tunnel used in the tests. It is entirely possible, and even likely, that one or more compensating errors resulting from simplifications used in the wind tunnel boundary corrections or scatter in the entire calibration data, to name just two possibilities, may have caused the agreement. It does suggest that further comparative testing over a wide range of shapes from high to low drag and over a range of model sizes in the case of the wind tunnel tests may lead to the establishment of a set of correlation factors or a theory which would increase the confidence level of road performance predictions made from the results of either sub- or full-scale wind tunnel tests.

5. CONCLUSIONS

1. Through the use of several simple add-on devices and minor design changes, drag reductions of from 20 to 25% were demonstrated on three large sales volume American automobiles. Effects on stability and handling were either neutral or favorable. Optimization of these approaches and investigation of others is expected to yield further significant drag reductions.

2. Agreement to about 4% was obtained between sub-scale and full-scale wind tunnel test results on a 1974 Mustang II notch-back coupe. Both sets of data were corrected for streamline curvature distortion in addition to the usual subsonic blockage and bouyancy corrections. This level of agreement may have been peculiar to the configuration and facilities involved, as the empirical and semi-empirical corrections of the order of 10% were applied to the sub-scale data.

3. Good agreement between full-scale wind tunnel and road test drag was obtained for a 1975 Chevrolet Impala. Here again, the level of agreement may have been peculiar to the specific vehicle tested. Generalizations from this single-point comparison must not be made until supported by additional comparisons.

4. The coast-down road test technique was demonstrated to be a practical method for obtaining high-quality drag data for real vehicles under actual operating conditions provided that sufficient care is taken with the details of the test technique.

6. RECOMMENDATIONS

While the results of the work reported herein have accomplished the purpose of this project as set forth in the Introduction, there are a number of recommendations for further work which should be implemented in order to achieve the general purposes of this project.

1) Excellent agreement between coast-down and full-scale wind tunnel test data was demonstrated for a standard and a low-drag configuration of one car. This comparison of test techniques should be extended to the full range of vehicle shapes, i.e., from subcompact shapes to large, blunt shapes such as the van, in order to determine the range over which such agreement can be expected or at least to develop correlation factors between the two techniques.

2) As better tire calibrations and information on the rolling resistance of the mechanical components is obtained, the coast-down data derived from vehicle tests should be reworked in order to more accurately establish the absolute values for the results.

3) Since subscale testing is and will continue to be an important tool in the development cycle of motor vehicles, more extensive comparative testing between subscale and full-scale models should be carried on in order to better understand the factors influencing the results in both cases. A set of somewhat simplified (to reduce cost) but representative standard models would be one approach to this study.

4) While the results presented in this report can be said to have achieved the objective of a 20-25% reduction of aerodynamic drag, only a very limited number of approaches were investigated, and even those were not fully optimized due to the limited scope of that phase of the project;

further gains are possible by including the other approaches and by a more thorough optimization of the devices and approaches tested here. Such work should be carried out in full-scale or subscale wind tunnel tests.

APPENDIX A
CORRECTIONS TO THE OBSERVED DATA

a. Blocking Corrections. The wind tunnel airstream velocity settings have been corrected for the increase in air velocity over the models due to Bernoulli's principle. This correction, which accounts for the increased velocity due to an effective reduction in test section area, is given by the following formula in terms of the tunnel setting parameter q:

$$q = q_u(1 + 2\varepsilon)$$

where ε is the sum of a solid blockage factor, dependent on the frontal area of the model at any given yaw angle, and a wake blockage factor, dependent on the size and velocity defect of the wake left by the model, and q_u is the dynamic pressure of the equivalent free airstream in the clear tunnel (no model) at the location of the model.

b. Buoyancy Corrections. The force and moment data presented in this report have been corrected for the effects of axial pressure gradients dp/dx in the wind tunnel test section without a model present. The buoyancy correction δC_D is added to the measured values of the wind axis drag coefficients and rotated into the stability axis system and corrects for the pressure drag resulting from the axial pressure gradients.

The equation used is

$$\delta C_D = \frac{1}{qA} \int_{\text{model}} \bar{A}\frac{dp}{dx}\, dx$$

Where A is the model local cross-sectional area, and x is the axial distance along the tunnel working section.

c. Streamline Curvature Corrections. Stability axis lift, drag, and pitching moment were corrected for streamline curvature effects on the wall and ceiling according to the method developed by Bettes and Kelly[6] as follows:

Ceiling and wall proximity parameters:

$B_1 = [\omega^2 + l_e{}^2]^{1/2} \sin [\tan^{-1}(\omega/l_e) + |\psi|]$

$B_r = B_1/B_o$

$H_r = H_1/H_o$

where

B_o = perpendicular distance between wind tunnel sidewalls

B_1 = distance between model lateral extremities measured normal to wind tunnel centerline

H_o = distance between test section floor and test section ceiling

H_1 = height of model above test section floor

l_e = overall length of model

ω = overall width of model

ψ = model angle of yaw (+ nose right)

Equations for lift, drag, and pitching moment corrections for wall and ceiling effects:

$C_{D_{corr}} = C_D - (dC_D/dB_r)B_r - (dC_D/dH_r)H_r$

$C_{L_{corr}} = C_L - (dC_L/dB_r)B_r - (dC_L/dH_r)H_r$

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[6] Bettes, W.H. and Kelly, K.B., "The Influence of Wind Tunnel Solid Boundaries on Automotive Test Data," Advances in Road Vehicle Aerodynamics 1973, pp.271-290, BHRA Fluid Engineering (1973).

TABLE A-1. DERIVATIVE VALUES OF STREAMLINE CURVATURE CORRECTION FOR SEDAN CONFIGURATIONS WITH COOLING SIMULATION

dC_L/dB_r	-0.070
dC_D/dB_r	+0.054
dC_m/dB_r	-0.035
dC_L/dH_r	-0.070
dC_D/dH_r	+0.082
dC_m/dH_r	-0.040

[a]From Bettes and Kelly (footnote 1).

$$C_{m_{corr}} = C_m - (dC_m/dB_r)B_r - (dC_m/dH_r)H_r$$

Derivative values are given in Table A-1. These experimentally derived corrections were applied with B_r and H_r limited to a maximum value of 0.333.

APPENDIX B
DATA REDUCTION OF COAST-DOWN DATA

B.1 PROGRAM DESCRIPTIONS

Four separate but interdependent computer programs are involved in the reduction of each run. In addition to the basic factors, the effects of lift, variable grade of the test roadway, realistic non-linear rolling resistance, and wind are all accounted for in this data reduction process. Wind was assumed steady for this study but variations during a run can be included. The four programs are identified by the names VEHCST-S, VEHVEL, VEHVEL-S, and VEHCD-E. A brief description of each program function follows. Figure B-1 is a flow diagram depicting the interrelationship of the four programs.

<u>VEHCST-S</u>. This is a specific version of a more general VEHCST program in that it handles a segmented-grade roadway such as the Edwards runway. Its purpose is to generate hypothetical coast-down data from known input. Necessary input information includes the initial velocity, the drag coefficient, tire rolling resistance characteristics, vehicle weight, and other pertinent roadway and atmospheric characteristics. The output is both a printout and punched deck of the resulting hypothetical coast-down history in the form of time, velocity, and distance. These arrival times at each of 11 stations 500 feet apart (corresponding to the actual stations in the road test) are in a format necessary for input to the VEHVEL program.

<u>VEHVEL</u>. This is a relatively simple program which converts the time-distance data to a time-velocity history with a three-point parabolic curve fit. Since the actual velocities are known for this case, the two are compared, and the differences are called "delta velocities." These deltas, computed for each station, are found to be a function of initial velocity, L/D ratio, tire rolling resistance, and roadway grade. The delta velocity groups are then used as corrections in processing the actual coast-down data.

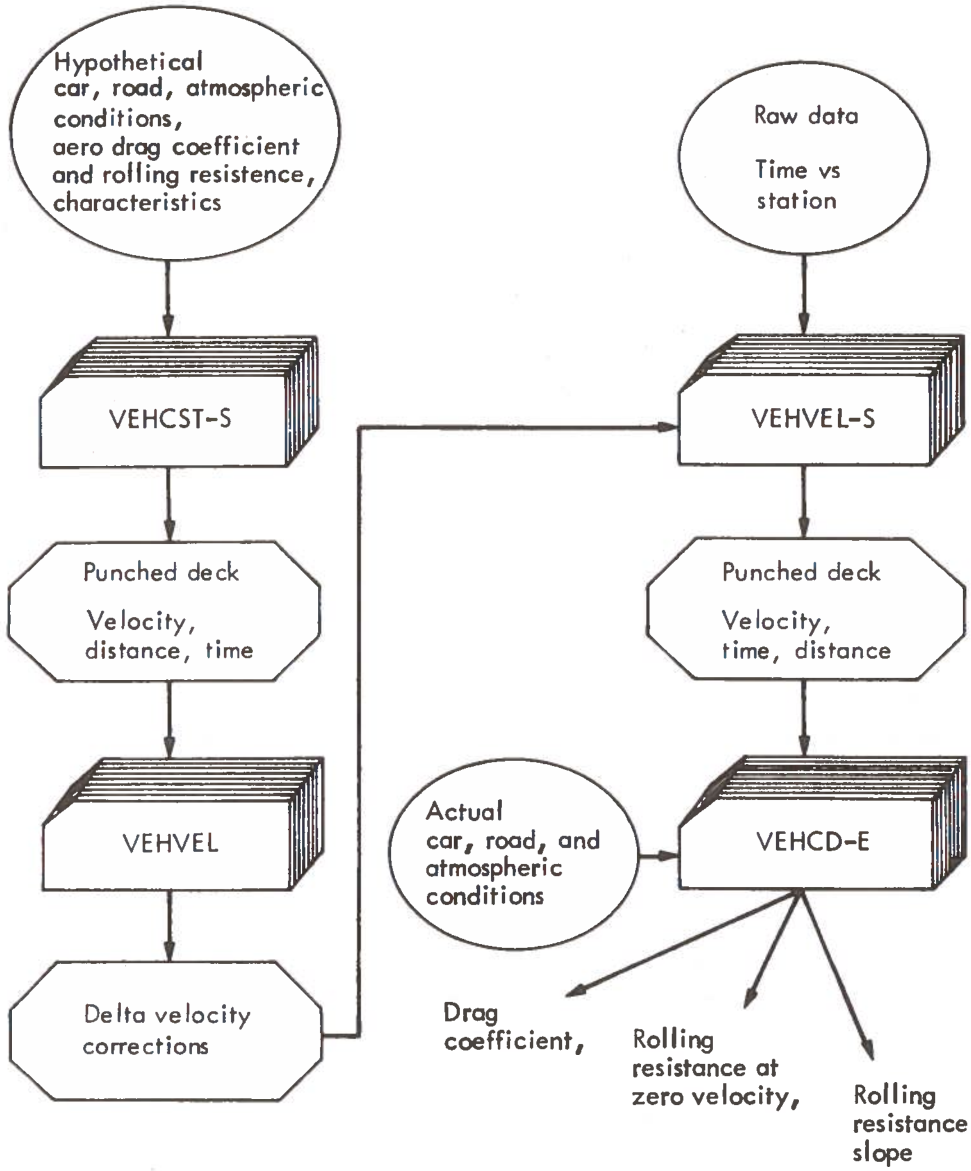

Figure B-1. Data Reduction Flow Chart

VEHVEL-S. As discussed earlier, the raw data are in the form of elapsed time between the 500-foot stations. This must first be converted to total elapsed time (zero at the initial station) versus distance and then input to the VEHVEL-S program with the "proper" set of delta velocities. VEHVEL-S then generates a printout and deck of corrected velocities versus time and distance in a format necessary for input to the VEHCD program.

VEHCD-E. This is the heart of the data reduction procedure. Its analytical approach is based on the work of White and Korst[7] which was extended by Dayman[8] to include experimental conditions such as lift, variable grade and non-linearities in the rolling resistance. It is a sophisticated program involving numerous iterative procedures. In addition to the corrected velocity history, the necessary input includes the vehicle roadway and atmospheric characteristics as well as iterative step sizes on C_D, C_R, and C_{RN} (drag coefficient, linear intercept level,[9] and linear slope of rolling resistance with velocity). The program can solve for all three simultaneously, but the computer computational time becomes high. Normally, one of the three is relatively known and can be fixed, which reduces the computer time by an order of magnitude. Depending on the step and matrix size called for, the program continues to pick pairs of C_D, C_R and C_{RN} to construct the best-fit curve through the data with the least RMS deviation. Much time was spent optimizing the step and matrix sizing to insure accuracy with minimum computer time.

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[7] White, R.A. and Korst, H.H., "The Determination of Vehicle Drag Contributions from Coast-Down Tests," SAE Paper 720099, 1972.

[8] Dayman, B., "Effect of Realistic Tire Rolling Resistance Upon the Determination of Aerodynamic Drag from Road-Vehicle Coast-Down Tests", presented at the 2nd AIAA Symposium on the Aerodynamics of Sports and competition Automobiles, Los Angeles, CA, May 1974.

[9] C_R is the level of the linear intercept and is not to be confused with the value of the rolling resistance coefficient at zero velocity.

B.2 APPROACH

Road tests were performed on five configurations of the Impala:

1) Standard with Firestone buffed tires at 28 psi.
2) Standard with Firestone buffed tires at 50 psi.
3) Standard with front windows down and Firestone buffed tires at 50 psi.
4) Standard with stock Uniroyal radial tires at 35 psi.
5) Low-drag configuration (N2/D3/L/-) with Firestone buffed tires at 50 psi.

The buffed Firestone tires had been drum calibrated before the road test at velocities from 20 to 60 mph and a pressure of 28 psi. The data were first reduced by 4% to account for drum curvature. Defining the rolling resistance coefficient (rolling resistance/load) to be $C_{RR} = C_R + C_{RN}V$, a linear regression analysis produced a value for C_{RN} at 28 psi. The additional effective rolling resistance due to the differential was experimentally determined, linearized, and combined with the tire results. The result is a value for the effective rolling resistance slope. Fixing C_{RN} in the VEHCD-E program for configuration 1 (above) yielded the drag coefficient for the Standard car. The rolling resistance characteristics of the Firestone buffed tires at 50 psi and the Uniroyal radial tires at 35 psi were inferred by fixing the drag coefficient and solving for C_R and C_{RN} on configurations 2 and 4, respectively. With tire characteristics determined under all test conditions, the drag coefficients of configurations 3 and 5 were calculated.

As a check on this procedure, the buffed tires were returned to Firestone for calibration of 50 psi. C_{RN} determined directly from these data indicated that the slope inferred from the data reduction procedure was low by almost 5%. With this information available, configurations 2, 3, and 5 were re-reduced using the Firestone calibration slope.

B.3 SENSITIVITY STUDY

A sensitivity study was performed in order to determine the sensitivity of the final drag coefficient to variations or uncertainties in the input. Some of the more important parameters investigated were wind, vehicle weight, slope of the linear rolling resistance, inclusion of a V^2 term in the rolling resistance slope, lift-to-drag ratio, and the ratio of the rotational kinetic energy of the tires and drive train to the translational kinetic energy.

The data reduction was performed with the assumption that the wind was steady and constant along the roadway during a run. A constant half-mile-an-hour uncertainty can affect the drag coefficient by -1.2% or + 1.5% for a head-or tailwind, respectively. A $\pm$1% uncertainty in vehicle weight results in a $\pm$1% uncertainty in C_D. Linearizing the slope of the rolling resistance term affects the C_D by only 0.1%, and changing the linearized slope of the same term by $\pm$6-1/2% changes C_D by $\mp$1%. The lift-to-drag ratio, when reduced from 1.0 to 0.5, has a -1.1% effect on C_D. An uncertainty of +0.01 in the kinetic energy ratio results in a +1.1% change in drag coefficient.

APPENDIX C
REPORT OF INVENTIONS

After a diligent review of the work performed under this contract, it was determined that no innovation, discovery, improvement, or invention was made.