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Assessment Of An Empirical Technique For Estimating Vehicle Aerodynamic Drag From Vehicle Shape Parameters

ASSESSMENT OF AN EMPIRICAL TECHNIQUE FOR ESTIMATING VEHICLE AERODYNAMIC DRAG FROM VEHICLE SHAPE PARAMETERS

by

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FOREWORD

This report, prepared by The Aerospace Corporation for the U.S. Environmental Protection Agency, Emission Control Technology Division, presents the results of a determination of aerodynamic drag coefficient, C_D, based on an empirical prediction technique developed by The Aerospace Corporation in a previous EPA-sponsored study. Values of C_D so determined are compared with C_D values derived from wind tunnel test data.

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SUMMARY

Aerodynamic drag coefficients for a fleet of twenty 1977/1978 model year passenger cars were derived using an empirical drag prediction technique previously developed for EPA by The Aerospace Corporation. This method utilizes an aircraft type "drag build-up" approach wherein the total drag is calculated as the sum of C_D contributions from various components of the vehicle.

The development of the aerodynamic drag coefficient using this method requires that an extensive data base of vehicle dimensions be determined. This was done by direct measurements in the field and from 8 x 10 photographs of the vehicles. To minimize distortion, photographs were taken from a distance of 100 meters using a telephoto lens in combination with a 35mm single lens reflex camera. The required projected areas were determined by planimetry from the photographs.

Results of the study indicate that the largest single contributor to the overall drag coefficient is the front end drag coefficient, C_{D_1}, which constitutes, on the average, about 29% of the total average drag coefficient. The other major contributors were found to be the base region drag coefficient, C_{D_5} (20%) and the front wheel and wheel well drag coefficient, C_{D_7} (26%).

Twelve of the twenty vehicles evaluated in this study were also tested by the Lockheed-Georgia Company in their Low Speed Wind Tunnel (LSWT). The LSWT test results were reported for two methods of wind tunnel blockage corrections: the area ratio method and the ceiling static pressure signature method. The latter blockage correction method resulted in 8% lower values of C_D than those based on the area ratio method.

A comparison of the LSWT test results based on the area ratio blockage correction method with the values derived in this study showed that nine of the twelve vehicles were within $\pm$ 10% of the wind tunnel test

results. The remaining three vehicles were found to be 12 to 18% lower than the wind tunnel results.

Wind tunnel test results based on the ceiling static pressure blockage correction method could be compared to five of the vehicles evaluated in this study. Calculated C_D's for four of these vehicles were within ±10% of the wind tunnel test results, while the C_D for the fifth vehicle was 16.5% higher than the wind tunnel test result.

The reasons for the differences with the wind tunnel results are not known precisely, although several potential sources of error have been identified which could have contributed to this lack of agreement. One is the lack of precision involved in the use of edge radius as a sole descriptor of vehicle contour in certain critical drag regions such as the vehicle front end. A second factor is the high degree of sensitivity of the results to the ratio of the edge radius and the projected length of that radius. Modifications to the calculation technique in these and other areas could improve the accuracy of the method.

A summary of the drag prediction method used in this study is given in Appendix A. Sample calculations and individual vehicle dimensions and areas are provided in Appendix B and C, respectively.

SECTION 1

INTRODUCTION AND BACKGROUND

The current federal test procedure for certification testing of light duty vehicles consists of running the vehicle on a dynamometer through a prescribed duty cycle. The power absorption unit of the dynamometer is adjusted according to a table of 50-mph road-load horsepower settings which are defined for a discrete set of loaded vehicle weights. Beginning with the 1979 model year, the method of determining the nominal dynamometer road load setting will be based primarily upon the vehicle reference frontal area (rather than vehicle inertia weight) and adjustments will be made according to whether the vehicle is classed as a fastback or non-fastback model (Ref. 1). Implicit in these procedures is the assumption that aerodynamic drag effects correlate simply with weight or frontal area and body type. Since, in general, the aerodynamic drag is variable with specific vehicle shape and contours as well as size, the ability to estimate the drag of individual vehicle configurations could provide an analytical basis for improving the accuracy of fuel consumption and exhaust emissions testing.

In a previous study for EPA (Ref. 2), the Aerospace Corporation developed an empirical technique which estimates the aerodynamic drag of road vehicles from various vehicle configuration parameters. The present study is directed toward the acquisition and application of vehicle measurements data as required to evaluate aerodynamic road load by this prediction method for comparison with measured values. The intent of this work is to test the relative accuracy of this prediction system as compared with the 1979 federal test procedure for determining dynamometer road load power absorption settings.

SECTION 2

ANALYTICAL APPROACH

The technique used to develop the aerodynamic drag coefficient is based on the method developed in The Aerospace Corporation report, "Estimation of Vehicle Aerodynamic Drag," Reference 2. This method consists of an aircraft-type "drag build-up" wherein the total drag is considered to be equal to the sum of the contributions of the various components of the vehicle. The individual equations for each C_D component, together with a definition of terms, are given in Appendix A for convenient reference. The development of the aerodynamic drag coefficient by this method requires that numerous vehicle physical dimensions be determined, including several projected areas, edge radii and associated lengths, and the slope of the windshield and hatch portions of the vehicle. The methods used to obtain the required dimensions and areas are discussed in Section 3.

A total of twenty 1977/1978 model year vehicles were investigated in the course of this study. Vehicles selected were based on a list of primary vehicle choices provided by the EPA. Characteristics of the individual vehicles are summarized in Table 2-1, including specific protuberances such as antenna, rear-view mirrors, etc., on each vehicle.

Table 2-1. Vehicle Characteristics

Manufacturer	Model Year	Make	Model	Body Style	Wheelbase	Protuberances
Chrysler	1977	Plymouth	Arrow	2-dr. Coupe	92.1	(1), (2)
	1977	Plymouth	Volare	Station Wagon	112.7	(1), (3), (4), (6)
	1978	Chrysler	LeBaron	4-dr. Sedan	112.7	(1), (3), (6)
	1978	Plymouth	Volare	Station Wagon	112.7	(1), (3), (4)
Ford	1977	Ford	Granada	4-dr. Sedan	109.4	(1), (5), (6)
	1977	Ford	LTD II	4-dr. Sedan	118.0	(1), (5), (6)
	1977	Ford	Mustang II	2-dr. Notch-back	96.2	(1), (5)
	1977	Ford	Pinto	3-dr. Runabout	94.5	(1), (5)
	1978	Ford	Fairmont	4-dr. Sedan	105.0	(1), (5), (6)
	1978	Ford	Granada	4-dr. Sedan	109.9	(1), (2), (6)
	1978	Ford	LTD II	4-dr. Sedan	114.0	(1), (2), (6)
General Motors	1977	Chevrolet	Impala	4-dr. Sedan	116.0	(5)
	1977	Chevrolet	Nova	4-dr. Sedan	111.0	(5)
	1977	Oldsmobile	Cutlass Supreme	2-dr. Coupe	112.0	(5), (6)
	1978	Chevrolet	Impala	4-dr. Sedan	116.0	(5)
	1978	Chevrolet	Monza	2-dr. Fastback	97.0	(2)
	1978	Chevrolet	Nova	4-dr. Sedan	111.0	(5)
	1978	Oldsmobile	Cutlass Supreme	2-dr. Coupe	108.1	(3), (6)
Porsche	1978	Porsche	924	2-dr. Coupe	94.5	(1), (5)
Volkswagen	1977	Volkswagen	Rabbit	2-dr. Hatch-back	94.5	(1), (3)

(1) External antenna
(2) Two bullet mirrors
(3) Two conventional mirrors
(4) Luggage rack
(5) One conventional mirror
(6) Hood ornament

SECTION 3

DATA BASE

As indicated in Appendix A, the development of the aerodynamic drag coefficient C_D using the drag build-up method requires that an extensive data base of vehicle dimensions be developed. This was done by direct measurement in the field and from 8 x 10 photographs of the vehicles.

3.1 DATA ACQUISITION

The numerous edge radii required to develop the various components of C_D as defined in Appendix A were obtained by direct measurements of the vehicles. For edge radii ≤ 0.75 inch, a series of fixed templates were used to match the vehicle contours. For edge radii > 0.75 inch, a flexible curve was fitted to the vehicle contour, transferred onto paper and matched to a known radius. The corresponding edge lengths were primarily determined by measurements from the photographs, as discussed in Section 3.2. If a true projected length (e.g., vertical length) could be measured in the field, it was recorded and served as confirmation of the value determined from the photograph.

The angle of inclination of the windshield and hatch portion, which are required in the evaluation of C_{D_2} and C_{D_5}, respectively, were measured with an inclinometer reading to the nearest 0.5 degree. The local horizontal at the vehicle was also determined in order to obtain the true angle of the windshield and hatch portion.

Direct field measurements were also made of antenna, hood ornaments, and radiator dimensions in order to determine their projected areas, since these could not be measured from the photographs.

The remaining required areas, as shown in Figure A-1, Appendix A, include the projected frontal area (A_R), the projected area of the front end (A_F), the projected area of the windshield (A_W), the projected area of the body below the hood-windshield intersection (A_h), the projected area of the flat portion of the base region (A_B), the projected area of the upper rear or hatch portion of the base region (A_H), and the projected area of various protuberances such as mirrors and luggage racks (A_{p_i}).

In addition to these projected areas, certain vehicle dimensions also had to be determined from the photographs. These included the projected length of the hood (L_h), the projected length (L) and width (W) of the vehicle underbody and the vehicle height (H).

In order to obtain the above required information, front, side, and rear views were taken of each vehicle from a distance of 100 meters. This camera-to-subject distance was selected on the basis of the recommendations presented in Reference 2, which indicates that a camera-to-subject distance of at least 100 meters should be used to minimize errors due to perspective.

Two reference panels having known dimensions and areas were included in each view, as indicated in Figures 3-1 to 3-3. For the front and rear views (Figures 3-1 and 3-2), panel number I, to the right of the vehicle, was located at a distance of 100 meters, in line with the front of the vehicle. Panel number II, on the left, was located at the mid-point of the wheelbase. In the side view (Figure 3-3), the near face of the vehicle was at 100 meters, with both panels located at the vehicle longitudinal center line.

Because of the necessity of taking both front/rear and side views of the vehicle and the approximate 2 to 1 vehicle dimensional disparity in these views, lenses of two different focal lengths were used in conjunction with an Olympus OM-1 35mm single lens reflex camera. For the side view, a 400mm focal length, f5.6 lens was used. For the front and rear views, the 400mm lens was used in combination with a 2X converter, which gave an effective focal length of 800mm. The objective in selecting these focal lengths was to obtain sufficient image size to minimize the degree of enlargement required in the 8 x 10 photographs. To minimize camera motion, the lens/camera was mounted on a tripod. In addition, the camera mirror was locked up prior to photographing the vehicle, and the shutter was tripped by the built-in shutter release.

Figure 3-1. 1977 Chevrolet Impala, Front View

Figure 3-2. 1977 Chevrolet Impala, Rear View

Figure 3-3. 1977 Chevrolet Impala, Side View

In order to adequately outline the underbody profile, a white panel was placed behind each vehicle in all three views.

Test photographs indicated that thermal effects could create an extreme image distortion effect, particularly on an asphalt surface. Accordingly, a concrete surface was selected in order to minimize this effect.

In addition to those photographs taken at a distance of 100m, three-quarter front and rear views were also taken of each vehicle using a standard 50mm lens from a distance of 5 to 10 feet in order to provide additional detail of front and rear body configurations and contours. Examples of these are shown in Figures 3-4 and 3-5.

3.2 DATA REDUCTION

Area measurements were made by planimetry, using a K & E Model 4242 Compensating Polar Planimeter. The planimeter was calibrated in terms of photo area (at a specific tracer arm setting) by use of the standard 10.00 in^2 Test Rule provided with the instrument. The calibration of actual (vehicle) area to photo area was obtained by determining the photo area of the 6.00 ft^2 reference panels (formed by a 54 in x 16 in rectangle). The latter area was found by measuring the height and width on the photo of the reference rectangle, and taking the product of photo height and photo width. This procedure was adopted because it was more rapid than planimetering the reference panels in the photo. Check measurements verified that both procedures gave the same results for the photo area of the reference panels.

For the front and rear views, reference panel I was located at the 100 meter line (adjacent to the front or rear bumper, respectively) while panel II was located on the other side of the car, at the midpoint of the wheel base. The reference panel(s) used in conjunction with each planimetered area are indicated in Table 3-2.

The notation (I + II)/2 means that the area calibration was taken to be the arithmetic average of the calibration factors determined for each

Figure 3-4. 1977 Chevrolet Impala, Front End Detail

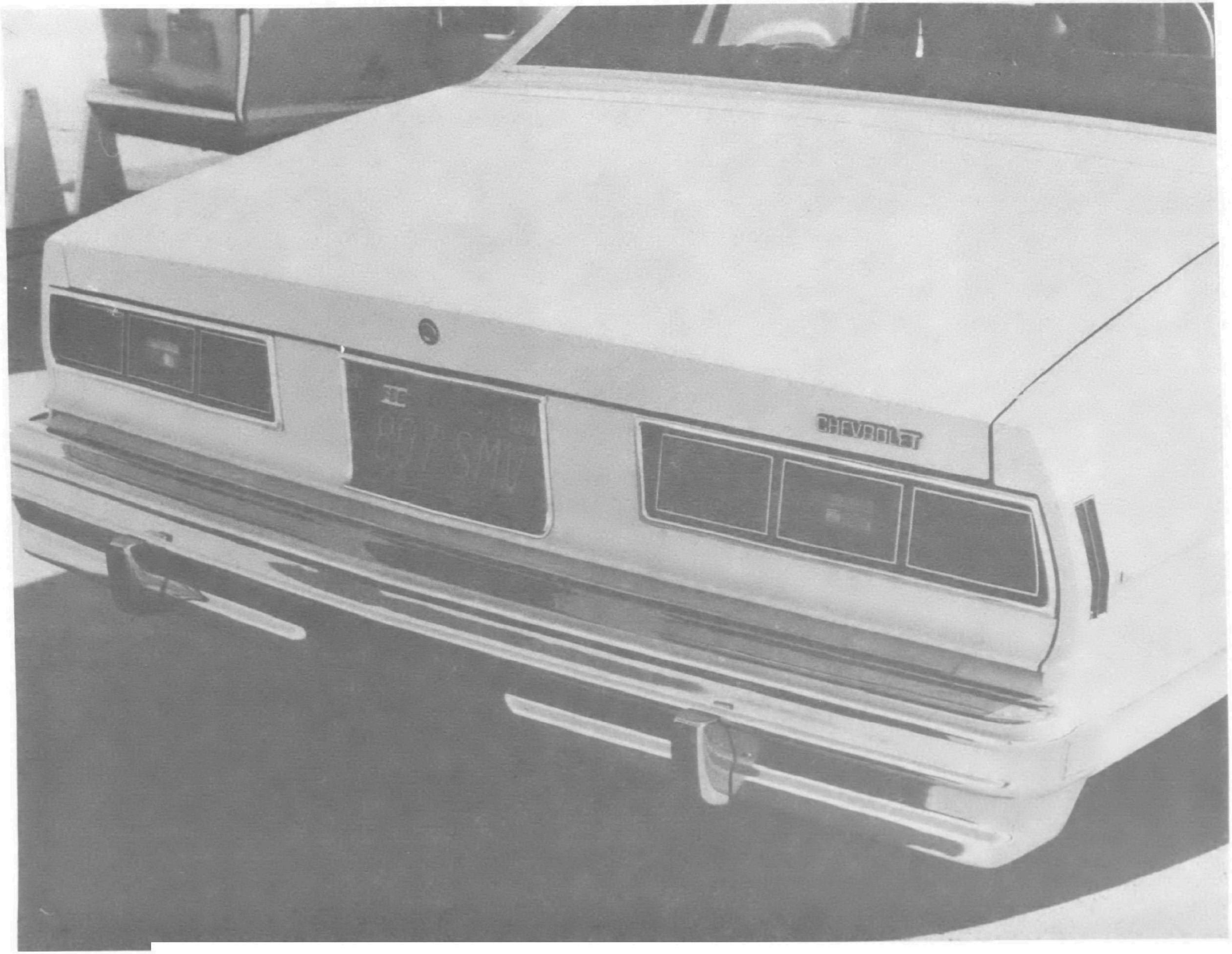

Figure 3-5. 1977 Chevrolet Impala, Rear Detail

Table 3-2. Reference Panel Assignment

Area	Symbol	Area Calibration Based on Panel(s)
	FRONT VIEW	
Reference	A_R	$\frac{I + II}{2}$
Hood and Front	A_h	$\frac{I + II}{2}$
Front	A_F	I
Windshield	A_W	II
Protuberance (Mirror or Luggage Rack)	A_{p_i}	II
	REAR VIEW	
Base	A_B	I
Hatch	A_H	
Non-Station Wagons		$\frac{I + II}{2}$
Station Wagons		I

panel. It is seen that the calibration factor for each planimetered area was based on the panel nearest to the segment of the vehicle defining that area. For an area defined by vehicle segments lying between the two panels, or comprised of sectors near each panel, the average calibration factor of the two panels was utilized. The rationale for this approach is illustrated by the case for vehicle frontal area A_R, as follows.

The selection of the average of Panels I and II for use as the calibration factor in determining the vehicle reference frontal area, A_R, was based on an assessment of the elements of the vehicle outline in the front view. For that portion of the vehicle below the front wheel well, the controlling perimeter is composed of the front wheel well, bumper, and front under carriage, all well forward of the Panel II location at the mid-point of the wheelbase and behind Panel I. Above the front wheel well, the controlling perimeter moves aft to the base of the windshield, then along the A-post and finally across the top of the vehicle (at or near the Panel II location). Thus, the controlling outline appears to range between Panel I and Panel II. If Panel II alone had been used in evaluating A_R, the calculated frontal area would have been, on the average, about 2% larger. An increase of 2% in A_R would have reduced C_D by about 1.5% and the product C_DA which is used in determining the aerodynamic drag force, would have been reduced by about 0.5%.

Reproducibility and precision of the planimetry was established by performing replicates of the planimetry operation for two cars, including the effect of varying the pole position for each measurement. Based on the results, the photo areas of the remaining vehicles were planimetered twice with additional measurements taken if the two readings differed by more than 1% and by more than 0.02 planimeter unit (the precision of reading was $\pm$0.01 planimeter unit).

Lengths were measured by engineering scale (60 divisions per inch) with the aid of an optical magnifier. The photo lengths were calibrated in terms of actual length by the previously measured photo length of one side of the reference rectangle. The reference panel (I or II) which was located closest to the dimension being measured was used. For the side view photos, an additional (and longer) reference length was provided by the field measurement of the spacing between the reference panels, both of which were the same distance from the camera. All photo measurements were made from 8 x 10 enlargements.

The basic definitions of the various length and area terms are defined in Appendix A. The specific definitions varied for each car, however, and were keyed to the actual vehicle geometry. For example, in order to establish the front end projected area A_F, it was necessary to define three aerodynamic "breaklines," i.e., front-hood, front-underbody and front-side. In some cases the definition of the breakline was evident; in other cases, however, complex trim and sheet metal contours made this decision more subjective. In these cases, a value judgment was made, based on field notes and measurements and the photographs (both long range and closeup detail shots). In any event, the objective of the procedure was to ensure that a common set of breaklines was used to define the various areas, lengths and radii of curvature for a given vehicle.

For the purpose of planning future work, it may be noted that the determination of the aerodynamic drag coefficient, C_D, using the drag build up technique employed in this study typically required about 8 hours per vehicle. Field data collection, including vehicle measurements and positioning the vehicle and reference panels for photographic purposes, required about 3 hours. Data reduction, including area determinations by planimetry and linear measurements from the photographs, and the determination of field measurements of the various radii of curvature required 3 to 4 hours, while the computations, including the length weighted R/E ratios and the C_D calculations, required an additional 1 to 2 hours.

SECTION 4

RESULTS

4.1 CALCULATED C_D VALUES

The individual components (C_{D_i}) of the total drag coefficient, C_D, were evaluated as outlined by the "drag build-up" method (Ref. 2) given in Appendix A. A sample calculation of these individual drag components for the 1977 Chevrolet Impala is shown in Appendix B.

The projected frontal area, A_R, the individual drag components, C_{D_1} - $C_{D_{11}}$, and the total drag coefficient, C_D for each of the test vehicles are summarized in Table 4-1.

Examination of these C_{D_i} components indicates that the largest single contributor to C_D is the front end drag coefficient, C_{D_1}, with an average value of about 0.154, or about 29% of the total average C_D. The contribution of the base region, C_{D_5} is about 0.105, or about 20% of the total. The third major contributor is the front wheel and wheel well drag coefficient C_{D_7}, taken to be a constant value of 0.140 (26% of the total C_D). These three components: C_{D_1}, C_{D_5}, and C_{D_7}; thus constitute, on the average, about 75% of the total C_D.

It will also be noted that the front end drag coefficient, C_{D_1}, encompasses the greatest vehicle-to-vehicle variation, ranging from 0.075 for the Porsche 924 to 0.228 for the 1978 Ford LTD II. In evaluating C_{D_1}, it was found that the results were extremely sensitive to the edge radii and associated edge lengths. Examination of Equation 1, Appendix A shows that of the three edge radii/length ratios, (R/E), the greatest weight is placed on $(R/E)_v$, relating to the vertical edge geometry. Because the vertical edge length, E_v, is considerably shorter than upper or lower edge lengths, the $(R/E)_v$ ratio is typically larger than the other two; i.e., $(R/E)_u$ and $(R/E)_l$. Hence, this ratio is generally dominant in the evaluation of C_D. And, since the vertical edge length was found to be quite similar on many of the domestic

Table 4-1. Summary of Results

Manufacturer	M. Y.	Make	Model	Body Style	Frontal Area, ft^2	C_{D_1} (Front End)	C_{D_2} (Wind-shield)	C_{D_3} (Front Hood)	C_{D_4} (Rear Vertical Edge)	C_{D_5} (Base Region)	C_{D_6} (Under-body)	C_{D_7} (Front Wheel Well)	C_{D_8} (Rear Wheel Well)	C_{D_9} (Protub-erances)	$C_{D_{10}}$ (Bullet Mirror)	$C_{D_{11}}$ (Radia-tor)		C_D (ΣC_{D_i})
Chrysler	1977	Plymouth	Arrow	2-dr. Coupe	17.82	0.185	0.017	0.014	-0.002	0.097	0.037	0.140	0.0	0.004	0.007	0.029		0.528
	1977	Plymouth	Volare	Station Wagon	22.76	0.133	0.046	0.013	-0.001	0.111	0.044	0.140	0.0	0.022	0.0	0.046		0.554
	1978	Chrysler	LeBaron	4-dr. Sedan	23.05	0.182	0.044	0.009	-0.002	0.111	0.044	0.140	0.0	0.014	0.0	0.049		0.585
	1978	Plymouth	Volare	Station Wagon	22.79	0.146	0.051	0.013	-0.001	0.108	0.044	0.140	0.0	0.023	0.0	0.041		0.565
Ford	1977	Ford	Granada	4-dr. Sedan	22.22	0.200	0.024	0.006	-0.003	0.107	0.044	0.140	0.0	0.008	0.0	0.049		0.575
	1977	Ford	LTD II	4-dr. Sedan	23.22	0.223	0.023	0.006	-0.002	0.099	0.045	0.140	0.0	0.008	0.0	0.054		0.596
	1977	Ford	Mustang II	2-dr. Notchback	19.29	0.145	0.019	0.011	-0.002	0.114	0.043	0.140	0.0	0.007	0.0	0.036		0.513
	1977	Ford	Pinto	3-dr. Runabout	19.46	0.100	0.031	0.022	-0.002	0.124	0.040	0.140	0.0	0.007	0.0	0.034		0.496
	1978	Ford	Fairmont	4-dr. Sedan	21.05	0.113	0.030	0.009	-0.002	0.110	0.042	0.140	0.0	0.009	0.0	0.052		0.503
	1978	Ford	Granada	4-dr. Sedan	22.18	0.214	0.028	0.007	-0.002	0.114	0.043	0.140	0.0	0.003	0.004	0.041		0.592
	1978	Ford	LTD II	4-dr. Sedan	23.23	0.228	0.021	0.005	-0.001	0.098	0.046	0.140	0.0	0.002	0.004	0.050		0.593
General Motors	1977	Chevrolet	Impala	4-dr. Sedan	24.14	0.179	0.029	0.010	-0.001	0.106	0.045	0.140	0.0	0.007	0.0	0.047		0.562
	1977	Chevrolet	Nova	4-dr. Sedan	22.56	0.106	0.026	0.012	-0.002	0.105	0.043	0.140	0.0	0.006	0.0	0.042		0.478
	1977	Oldsmobile	Cutlass	2-dr. Coupe	22.62	0.157	0.032	0.016	-0.001	0.103	0.043	0.140	0.0	0.009	0.0	0.044		0.543
	1978	Chevrolet	Impala	4-dr. Sedan	23.89	0.170	0.031	0.009	-0.001	0.108	0.046	0.140	0.0	0.006	0.0	0.048		0.557
	1978	Chevrolet	Monza	2-dr. Fastback	19.04	0.165	0.017	0.027	-0.004	0.084	0.041	0.140	0.0	0.0	0.005	0.036		0.511
	1978	Chevrolet	Nova	4-dr. Sedan	22.77	0.093	0.024	0.012	-0.002	0.105	0.041	0.140	0.0	0.007	0.0	0.042		0.462
	1978	Oldsmobile	Cutlass	2-dr. Coupe	21.58	0.149	0.019	0.019	-0.001	0.118	0.042	0.140	0.0	0.013	0.0	0.048		0.547
Porsche	1978	Porsche	924	2-dr. Sport Cpe	18.88	0.075	0.018	0.055	-0.008	0.073	0.039	0.140	0.0	0.011	0.0	0.027		0.430
Volkswagen	1977	Volkswagen	Rabbit	2-dr. Hatchback	19.77	0.111	0.035	0.037	-0.002	0.102	0.031	0.140	0.0	0.009	0.0	0.026		0.489

cars, the value of this ratio was largely dependent on the value of the vertical edge radius in the fender/headlight region. It is believed that this particular edge radius was largely responsible for the variation seen in C_{D_1}.

4.2 COMPARISON WITH WIND TUNNEL RESULTS

Twelve of the twenty vehicles evaluated in this study were also tested by the Lockheed-Georgia Company, Marietta, Georgia in the Low Speed Wind Tunnel (LSWT), as reported in References 3 and 4. Wind tunnel test results were given in Reference 3 for eight of the 12 vehicles and were based on the area ratio method of determining the wind tunnel blockage correction. In this method, the test section blockage is computed as a function of the ratio of automobile frontal area to test section cross section area; i.e., $K = 1/2\ (S/C)$, where S is the automobile frontal area* and C is the test section cross sectional area.

Lockheed subsequently reported (Ref. 4) that studies of wind tunnel blockage methods showed that the conventional area ratio method under-corrects blockage and buoyancy for bluff bodies such as automobiles, due to large wake effects. A method of accounting for the large wake, derived by the Lockheed-Georgia Company, uses the test section ceiling static pressure distribution to arrive at the blockage correction. For this ceiling static pressure signature method, test section static pressures along the ceiling centerline are measured with the model both in and out of the test section. Lockheed reported that a comparison of the data using the two blockage methods showed that coefficient data based on the area ratio method are higher than those based on the ceiling static pressure signature method by 2.8 to 12 percent for the range of vehicles tested (Ref. 4).

Reference 4 provides wind tunnel test results for four additional vehicles examined in this study as well as a retest of the 1977 Ford Granada reported in Reference 3. The data presented are based on both the area ratio blockage correction method and the ceiling pressure signature method.

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*Lockheed values of frontal area were generally within ± 1 percent of values determined by Aerospace.

A comparison of the LSWT test results with the values derived in this study are shown in tabular form in Table 4-2 and graphically in Figure 4-1. The wind tunnel test results were given in terms of $C_D A$ and were derived from F_D/Q, where F_D is the drag force in pounds and Q is the dynamic pressure in lb/ft^2. The values of C_D shown for the wind tunnel results were derived by dividing the reported value of $C_D A$ by the projected frontal area, A_R, as determined by the present study.

As indicated in Table 4-2, the calculated values of C_D developed in this study average 5.0% lower than the wind tunnel results based on the area ratio blockage correction method and 5.9% higher than the wind tunnel results based on the ceiling static pressure signature method. Thus, on average, the calculated values of C_D would appear to be in good agreement with the wind tunnel results. As indicated in Table 4-2, however, the data also shows a high degree of dispersion; the standard deviation of the area ratio data set is 8.1% compared to a mean deviation of -5.0%, while the static pressure data set shows a standard deviation of 7.4% compared to a mean deviation of 5.9%. The dispersion in the area ratio set is due primarily to the results obtained for the Pinto, the Mustang II, the 1978 Volare Station Wagon, and to a lesser degree, to the Porsche 924. In the case of the static pressure data set, the primary outlier is the 1978 Le Baron. Further discussion of these outliers is provided below.

The vehicles which show the greatest disagreement with the area ratio wind tunnel results are the Pinto (-18.4%), the Mustang II (-16.9%), the 1978 Volare Station Wagon (-11.9%), and the Porsche 924 (+8.3%). In the case of the Pinto, an examination of the individual components of C_D given in Table 4-1 shows that C_{D_1}, the front end drag coefficient, is one of the lowest in the data set. This value is due primarily to the large (6 in.) upper edge radius, R_u, above the grille at the hood-front breakline. The Mustang II, however, does not show any single component of C_D that is noticeably lower than the other vehicles. Similarly, the disagreement indicated for the 1978 Volare Wagon is not explainable in terms of component drag peculiarities. It should be noted that calculated C_D values for the 1978 model Volare are

Table 4-2. Comparison of Calculated Aerodynamic Characteristics with Wind Tunnel Test Results

Vehicle	Calculated Results: Projected Frontal Area, A_R ft^2	Calculated Results: C_D [2]	Calculated Results: C_DA [2]	Wind Tunnel Results, Area Ratio Blockage Method: C_D [2],[3]	Wind Tunnel Results, Area Ratio Blockage Method: C_DA [2]	Wind Tunnel Results, Pressure Signature Blockage Method: C_D [2],[3]	Wind Tunnel Results, Pressure Signature Blockage Method: C_DA [2]	% Δ C_D [1]: Area Ratio Method	% Δ C_D [1]: Pressure Signature Method
'77 Chevrolet Impala	24.14	0.562	13.54	0.588	14.16[4]			-4.4	
'77 Ford Granada	22.22	0.575	12.77	0.602	13.36[4]			-4.5	
'77 Ford Granada				0.580	12.88[5]	0.535	11.90[5]	-0.9	+7.5
'77 Ford Mustang II	19.29	0.513	9.90	0.617	11.90[4]			-16.9	
'77 Ford Pinto	19.46	0.496	9.67	0.608	11.85[4]			-18.4	
'77 Plymouth Arrow	17.82	0.528	9.40	0.545	9.70[4]			-3.1	
'77 Plymouth Volare Wagon	22.76	0.554	12.63	0.558	12.72[4]			-0.7	
'77 Porsche 924	18.88	0.430	8.13	0.397	7.50[4]			+8.3	
'77 VW Rabbit	19.77	0.489	9.64	0.523	10.36[4]			-6.5	
'78 Chevrolet Impala	23.89	0.557	13.31	0.577	13.79[5]	0.521	12.45[5]	-3.5	+6.9
'78 Plym. Volare Wagon	22.79	0.565	12.88	0.641	14.61[5]	0.584	13.31[5]	-11.9	-3.3
'78 Chrysler LeBaron	23.05	0.585	13.48	0.545	12.57[5]	0.502	11.58[5]	+7.3	+16.5
'78 Cutlass Supreme	21.58	0.547	11.80	0.580	12.51[5]	0.538	11.61[5]	-5.7	+1.7
							Mean % Δ C_D	-5.0	+5.9
							Standard Deviation, σ	8.1	7.4

[1] (calc. - W. T.)/W.T.

[2] At 50 mph.

[3] Derived from C_DA/A_R

[4] Reference 3

[5] Reference 4

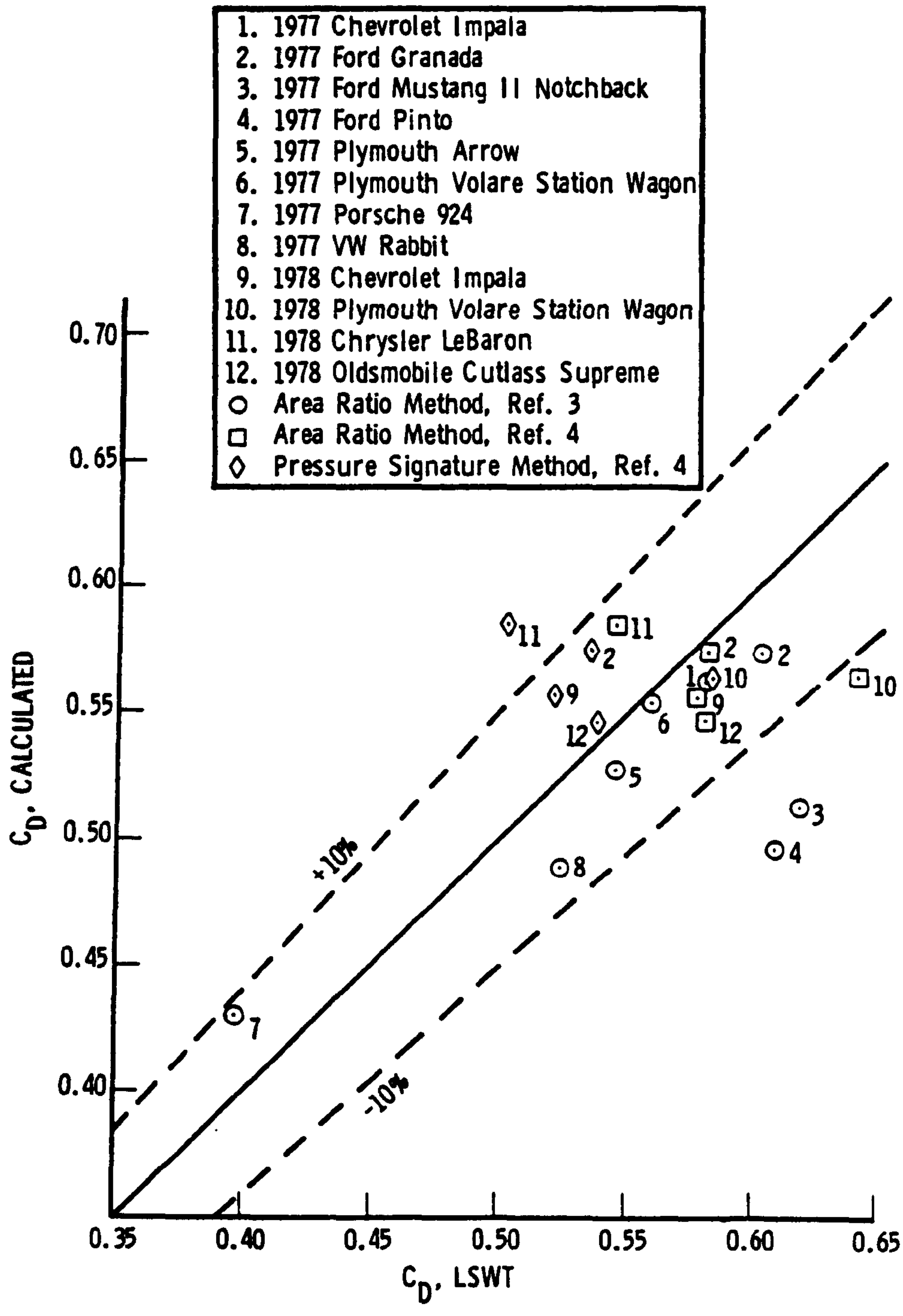

Figure 4-1. Comparison of Test and Calculated Values of Aerodynamic Drag Coefficient

very similar to those for the 1977 model, which showed excellent agreement with the test result (-.7%). The similarity in component C_D's would be expected in view of the minor styling changes between the two model years.

The value of C_D derived for the Porsche 924 was found to be extremely sensitive to the front hood configuration and the related effects on C_{D_1} and C_{D_3}. The values of C_{D_1} and C_{D_3} shown in Table 4-1 were based on the assumption that the front of the hood began at the top edge of the front bumper. The selection of this line of demarcation resulted in the low value (0.075) for C_{D_1} and the comparatively high value (0.055) for C_{D_3}. Examination of the front end detail of the Porsche 924, shown in Figure 4-2, suggests the possibility of using an alternate breakline between the hood and front end; that is, the line of intersection of two planes on the hood. This breakline would result in a larger front end area, A_F, and a smaller hood area (A_h - A_F). The net effect would be to reduce C_{D_3} by 0.010. The net effect on C_{D_1}, however, is difficult to assess since an effective upper edge radius, R_u, cannot be determined. As seen in Figure 4-2, this front-hood breakline is essentially the intersection of two planes, with a very small radius of curvature (i.e., 1/16 in.) at the point of intersection. However, since the angular change at this breakline is on the order of 25 to 30°, it would seem that some larger effective upper edge radius should be used. Indicative of the sensitivity of C_{D_1} to this upper edge radius is the net change in C_{D_1} which occurs when the value of R_u is altered. If, for example, the value of 1/16 in. were used, C_{D_1} would increase by 0.024 over that shown in Table 4-1. If, on the other hand, a value of say 6 in. were assumed, C_{D_1} would be reduced by 0.040.

Based on the foregoing discussion, it would appear that the derived value of C_D for the Porsche may be too high, although any revision to the derived value would require a more definitive assessment of the upper edge radius than is provided for in the technique used in this study.

Of the five vehicles available for comparison with the wind tunnel data based on the ceiling static pressure blockage correction method, the

Figure 4-2. Porsche 924, Front End Detail

1978 Chrysler Le Baron shows the greatest disagreement; the calculated value is 16.5% higher than the wind tunnel results. An examination of the individual C_D components for this vehicle (Table 4-1) does not reveal any significant differences from the other vehicles. Hence, the reason(s) for the discrepancy in results is not apparent.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

The aerodynamic drag coefficient, C_D, as developed by the "drag build-up" method, was determined for a total of twenty 1977/1978 model year vehicles. Results of the low speed wind tunnel tests conducted by the Lockheed-Georgia Company (based on an area ratio blockage correction method) on twelve of the vehicles were available for comparison, and showed that the empirically derived value of C_D for nine of the twelve vehicles was within ±10% of the wind tunnel results. Of these nine vehicles, the value of C_D determined for the Porsche must be considered somewhat suspect in view of the uncertainties in defining the hood-front breakline and the associated edge radius. The other three vehicles (the Mustang II, Pinto, and 1978 Volare station wagon) were found to be 12 to 18% lower than the wind tunnel results. The reason for this difference is not apparent in the case of the Mustang II and Volare. The low value of C_D calculated for the Pinto may be due in part to its low value of C_{D_1} (0.100) which derives from the large edge radius (6 in.) at the hood-front breakline above the grille.

Wind tunnel test results using the ceiling static pressure signature blockage correction method were available for comparison for five of the vehicles evaluated. The empirically derived C_D values for four of the five vehicles were also within ±10% of the wind tunnel results. The value of C_D for the remaining vehicle (the Le Baron) was found to be 16.5% higher than the wind tunnel results.

In summary, the empirical evaluation of the vehicle aerodynamic drag coefficient by the drag build-up method showed good agreement with the wind tunnel results in most, but not all, cases. Several factors are believed to have contributed to the lack of agreement. One is the subjective interpretation required in evaluating certain edge radii. A second factor is the high degree of sensitivity of the results to the ratio of the edge radius to the projected length of that radius (R/E). This factor was found to be particularly important in the case of C_{D_1}, but it also affected the evaluation of C_{D_2} and C_{D_4}, although to a lesser degree. While this effect was recognized in developing the equations for evaluating the forebody drag components (Ref. 2), the results of this study suggest that the method could be improved by modifying some of the simplifying assumptions made in defining the effect of rounded edges.

Beginning with 1979 model year vehicles, the method used by EPA for establishing dynamometer power absorption settings for emission certification and fuel economy testing of light duty vehicles will be based on vehicle equivalent inertia weight, vehicle reference frontal area, and vehicle protuberances, using a formula in which aerodynamic drag road load effects are approximated by the relation

$$HP = cA + P$$

where A is the vehicle projected frontal area, c is a constant which has different values for fastback and non-fastback vehicles, and P is a protuberance factor. This equation implicitly assumes that the contribution to the aerodynamic drag coefficient from the vehicle body (excluding protuberances) is equal (constant) for all vehicles in each configuration category.

Using C_D's developed from the above relation, the accuracy of assuming constant drag coefficients can be evaluated and compared to the accuracy of the drag coefficient buildup method of this report. However, it must be noted that the wind tunnel testing, which encompasses two different blockage correction methods, provides comparable data for only five of the 20 vehicles evaluated in this study (see Table 4-2). This small sample size precludes a rigorous statistical analysis of the accuracy of the methods.

For the five vehicles that can be compared to both sets of wind tunnel results, a simple computation of the average disparity* between C_D calculated

*defined as $\sum |\% \Delta C_D| / N$

and C_D tested yields (a) 6.2% and 7.2% for the drag buildup method as referenced to the area ratio and pressure signature blockage correction test results, respectively, and (b) 3.3% and 10.5% for corresponding values derived from the EPA dynamometer relation. Slight differences in numerical values notwithstanding, the significant aspect of this result is that the disparities are small and similar in magnitude for the two methods. Thus, for this specific set of five vehicles, the use of a relation based on a constant average C_D for the vehicle body with correction for protuberances appears to provide as accurate a prediction of the vehicle C_D as is obtained from the drag coefficient buildup approach.

It is concluded that the data developed in this study does not indicate an increase in the accuracy of predicting drag coefficient using the drag coefficient buildup approach compared with the accuracy obtained by assuming a constant average drag coefficient for all similar vehicles. Therefore, no changes to the current relation defining dynamometer road load horsepower settings are recommended on the basis of the present work.

REFERENCES

1. Federal Register, Vol. 42, No. 176, September 12, 1977.

2. Estimation of Vehicle Aerodynamic Drag, Aerospace Report No. ATR-77(7359-1), The Aerospace Corporation, El Segundo, California, October 1976.

3. E. A. Payne, Low Speed Wind Tunnel Test to Determine the Aerodynamic Characteristics of Thirteen Automobiles, Report No. LSWT 211, Lockheed-Georgia Company, Marietta, Georgia, May 1977.

4. D. L. Bruce, Determination of Automobile Aerodynamic Characteristics, Low Speed Wind Tunnel Tests, Lockheed-Georgia, Company, Marietta, Georgia, June 1978.

APPENDIX A

DRAG PREDICTION METHOD

The drag prediction technique developed by The Aerospace Corporation in Reference 2 breaks the drag of a road vehicle into 11 discrete contributions. The reference area, A_R, which is used to normalize the component drag contributions, is taken to be the projected frontal area of the vehicle including tires and underbody details but excluding protuberances such as mirrors, antenna, and luggage carriers. The contribution of a component is a function of its size so that typically a representative area A_i of each component, as well as A_R, appear in the formulas. The relevant vehicle dimensions and areas are illustrated in Figure A-1. The details of the drag build-up are presented in the following pages.

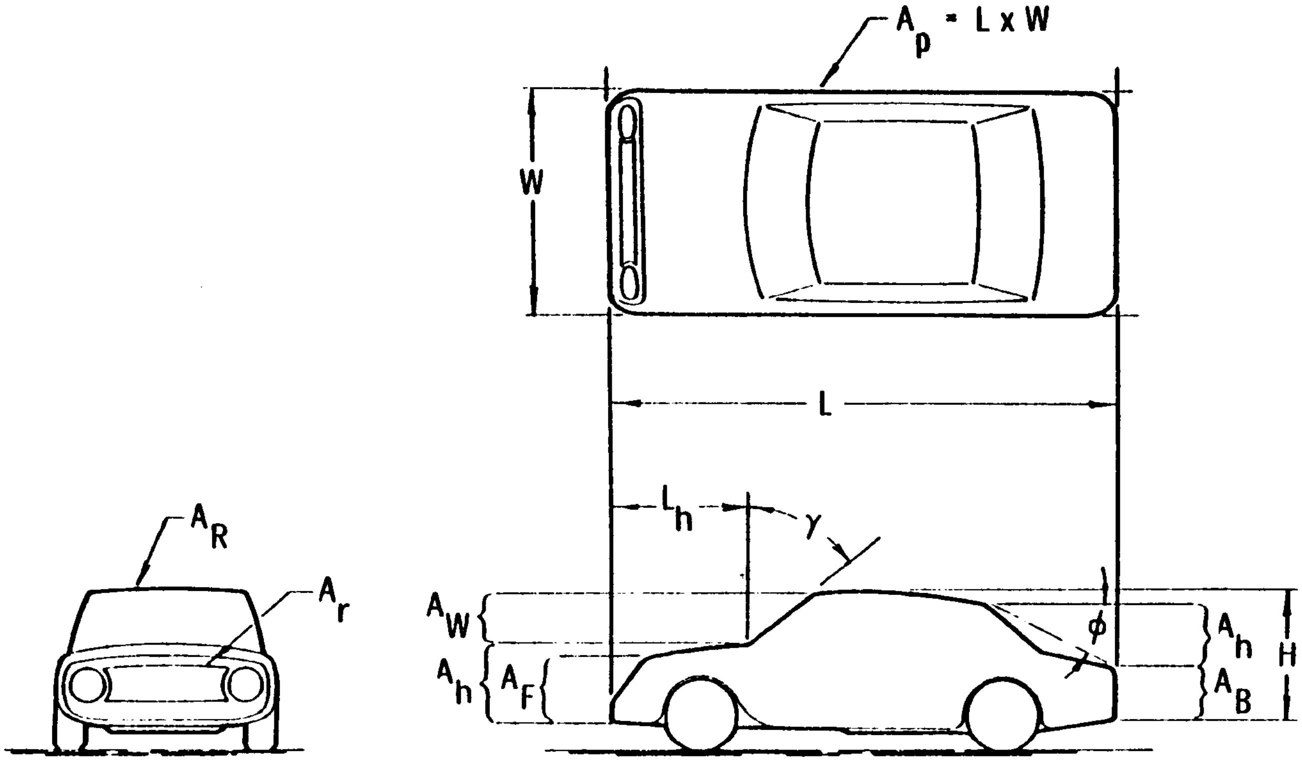

Figure A-1. Vehicle Dimensions

Front End Drag Coefficient, C_{D_1}—

$$C_{D_1} = 0.707\left(\frac{A_F}{A_R}\right)\left\{1.0 - 2.79\left(\frac{R}{E}\right)_u + 0.82\left(\frac{R}{E}\right)_l - 5.21\left(\frac{R}{E}\right)_v - 29.5\left(\frac{R}{E}\right)_u\left(\frac{R}{E}\right)_l\left[1.0 - 2.25\left(\frac{R}{E}\right)_v\right]\right\} \quad (1)$$

where

A_R = projected frontal area of the vehicle including tires and underbody details, m^2 (ft^2)

A_F = front end projected area, m^2 (ft^2)

R = edge radius, m (ft)

E = projected length of the edge radius, m (ft)

and the subscripts u, l, and v refer to the upper, lower, and vertical edges of the front end, respectively. The $(R/E)_i$ are to be taken as 0.105 when the estimated values exceed this magnitude.

Windshield Drag Coefficient, C_{D_2}—

$$C_{D_2} = 0.707\left(\frac{A_W}{A_R}\right)\left[1.0 - 2.79\left(\frac{R}{E}\right)_{u'}\cos\beta - 5.21\left(\frac{R}{E}\right)_{v'}\right]\cos^2\gamma \quad (2)$$

where

A_W = projected area of windshield, m^2 (ft^2)

γ = slope of the windshield measured from the vertical, deg

β = 2γ

and the subscripts u' and v' refer to the roof-windshield intersection and the windshield posts, respectively. The value of $\cos\beta$ is to be taken as zero for γ larger than 45° and the $(R/E)_i$ are to be taken as 0.105 for estimated values exceeding this magnitude.

Front Hood Drag Coefficient, C_{D_3}—

$$C_{D_3} = 0.707\left(\frac{A_h - A_F}{L_h}\right)^2 \Big/ A_R \tag{3}$$

where

A_h = projected area of body below the hood-windshield intersection, m^2 (ft^2)

L_h = length of hood in the elevation or side view, m (ft)

and the quantity $(A_h - A_F)$ is to be taken as zero if it is negative.

Rear Vertical Edge Drag Coefficient, C_{D_4}—

$$C_{D_4} = \left.\begin{array}{ll} -0.19\left(\frac{R_v}{W}\right)\left(\frac{E_b}{H}\right) & \text{for } \left(\frac{R_v}{W}\right) \leq 0.105 \\ = -0.02\left(\frac{E_b}{H}\right) & \text{for } \left(\frac{R_v}{W}\right) > 0.105 \end{array}\right\} \tag{4}$$

where

R_v = radius of rear vertical edges, m (ft)

W = projected width of rear vertical portion, m (ft)

E_b = projected length of rear vertical edge radius, m (ft)

H = vehicle height, m (ft)

Base Region Drag Coefficient, C_{D_5}—

$$C_{D_5} = 0.15\left[\left(\frac{A_B}{A_R}\right) + \left(\frac{C_{D_H}}{C_{D_B}}\right)\left(\frac{A_H}{A_R}\right)\right] \tag{5}$$

where

A_B = projected area of flat portion of base region

A_H = projected area of upper rear or hatch portion of base region measured from the upper rear roof break (or for smoothly curved rooflines, that point where the roofline slope is 15^o) to the top of the flat base, m^2 (ft^2)

C_{D_B} = drag coefficient of the flat base

C_{D_H} = drag coefficient of the upper rear or hatch portion of the base region

and the ratio (C_{D_H}/C_{D_B}) is shown in Figure A-2 as a function of ϕ, the angle of the line from the upper rear roof break to the top of the flat base as measured from the horizontal.

Underbody Drag Coefficient, C_{D_6}—

$$C_{D_6} = 0.025\,(0.5 - x/L)\left(\frac{A_p}{A_R}\right) \quad \text{for } 0 \le x/L \le 0.5 \qquad (6)$$
$$= 0 \quad \text{for } x/L > 0.5$$

where

x = smoothed forward length of the underbody, m (ft)

L = vehicle underbody length, m (ft)

A_p = projected plan area of the vehicle underbody, m^2 $(ft)^2$

Wheel and Wheel Well Drag Coefficient, C_{D_7}—

$$C_{D_7} = 0.14 \qquad (7)$$

Rear Wheel Well Fairing Drag Coefficient, C_{D_8}—

$$C_{D_8} = -0.01 \text{ for rear wheel well covered} \qquad (8)$$
$$C_{D_8} = 0.0 \text{ for real wheel well not covered}$$

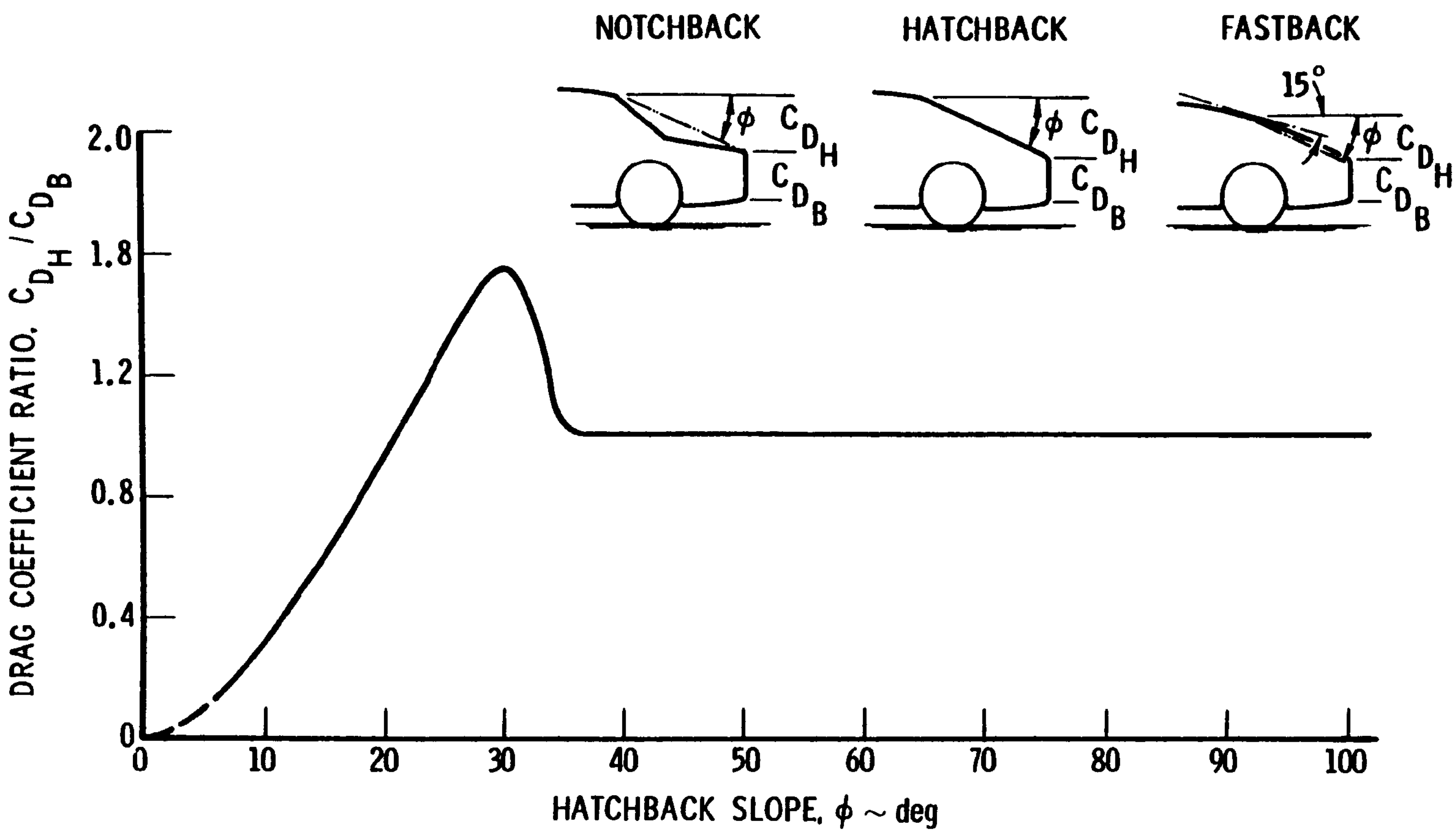

Figure A-2. ***Hatchback-Notchback Drag Coefficient Ratio***

Protuberance Drag Coefficient, C_{D_9}—

$$C_{D_9} = \frac{1.1}{A_R} \sum A_{p_j} \qquad (9)$$

where

A_{p_j} = projected area of jth protuberance, m^2 (ft^2)

Bullet Mirror Drag Coefficient, $C_{D_{10}}$—

$$C_{D_{10}} = 0.4 \frac{A_M}{A_R} \qquad (10)$$

where

A_M = projected area of mirror with bullet fairing, m^2 (ft^2)

Cooling Drag Coefficient, $C_{D_{11}}$—

$$C_{D_{11}} = 1.8 \left(\frac{A_r}{A_R}\right)\left(\frac{u_r}{u}\right)\left[1.0 - 0.75\left(\frac{u_r}{u}\right)\right] \qquad (11)$$

where

A_r = radiator area, m^2 (ft^2)

u_r = exit velocity of cooling air from radiator, m/sec (mph)

u = vehicle speed, m/sec (mph)

(u_r/u) = $0.233 [1.0 - k (u/100)^2]$

and

k = $1.146 \ (m/sec)^{-2}$ [or $0.229 \ (mph)^{-2}$]*

*Represents a correction to Ref. 2, published as .299.

APPENDIX B

Sample Calculation

Vehicle 1977 Impala

License No. 807SMV

C_{D_1}:

R_u 1.625 in. $(R/E)_u$ 0.0248 (max. = 0.105)

E_u 65.45 in.

R_ℓ 0.935 in. $(R/E)_\ell$ 0.0137 (max. = 0.105)

E_ℓ 68.41 in.

R_v 1.029 in. $(R/E)_v$ 0.0580 (max. = 0.105)

E_v 17.74 in.

A_F 9.657 ft^2

A_R 24.137 ft^2 (A_F/A_R) 0.4001

$$C_{D_1} = 0.707\left(\frac{A_F}{A_R}\right)\left\{1.0 - 2.79\left(\frac{R}{E}\right)_u + 0.82\left(\frac{R}{E}\right)_\ell - 5.21\left(\frac{R}{E}\right)_v - 29.5\left(\frac{R}{E}\right)_u\left(\frac{R}{E}\right)_\ell\left[1.0 - 2.25\left(\frac{R}{E}\right)_v\right]\right\}$$

$$C_{D_1} = 0.1785$$

C_{D_2}:

$R_{u'}$ 2.5 in. $(R/E)_{u'}$ 0.0496 (max. = 0.105)

$E_{u'}$ 50.43 in.

$R_{v'}$ 1.5 in. $(R/E)_{v'}$ 0.0982 (max. = 0.105)

$E_{v'}$ 15.28 in.

Sample Calculation (Continued)

$\underline{C_{D_2}}$ (Cont'd)

γ 53° $\qquad \beta = 2\gamma = 106°$ $\qquad (\cos\beta = 0 \text{ for } \gamma > 45°)$

A_W 5.517 ft²

A_R 24.137 ft² $\qquad (A_W/A_R)$ 0.2286

$$C_{D_2} = 0.707\left(\frac{A_W}{A_R}\right)\left[1.02 - 2.79\left(\frac{R}{E}\right)_{u'}\cos\beta - 5.21\left(\frac{R}{E}\right)_{v'}\right]\cos^2\gamma$$

$$C_{D_2} = 0.0286$$

$\underline{C_{D_3}}$:

A_h 12.708 ft² $\qquad L_h$ 5.118 ft

A_F 9.657 ft² $\qquad A_R$ 24.137 ft²

$$C_{D_3} = 0.707\left[\frac{(A_h - A_F)}{L_h}\right]^2 \Big/ A_R$$

$$C_{D_3} = 0.0104$$

$\underline{C_{D_4}}$:

R_v 0.854 in. $\qquad (R_v/W)$ 0.0127

W 67.08 in.

E_b 18.65 in. $\qquad (E_b/H)$ 0.4327

H 43.10 in.

$$C_{D_4} = -0.19\left(\frac{R_v}{W}\right)\left(\frac{E_b}{H}\right) \qquad \text{for } \left(\frac{R_v}{W}\right) \le 0.105$$

$$= -0.02\left(\frac{E_b}{H}\right) \qquad \text{for } \left(\frac{R_v}{W}\right) > 0.105$$

$$C_{D_4} = 0.0010$$

C_{D_5}:

A_B 9.157 ft^2 $\quad$ A_B/A_R 0.3794

A_R 24.137 ft^2

ϕ 20° $\quad$ C_{D_H}/C_{D_B} 0.925 (f (ϕ), from Fig. A-2)

A_H 8.629 ft^2 $\quad$ A_H/A_R 0.3575

$$C_{D_5} = 0.15\left[\left(\frac{A_B}{A_R}\right) + \left(\frac{C_{D_H}}{C_{D_B}}\right)\left(\frac{A_H}{A_R}\right)\right]$$

$$C_{D_5} = 0.1065$$

C_{D_6}:

x 0 $\quad$ x/L 0

L 211.50 in. $\quad$ A_p (=L x W) 86.00 ft^2

W 58.55 in.

$$C_{D_6} = 0.025\ (0.5 - x/L)\left(\frac{A_p}{A_R}\right) \quad \text{for } 0 \leq x/L \leq 0.5$$

$$C_{D_6} = 0 \quad \text{for } x/L > 0.5$$

$$C_{D_6} = 0.0445$$

$$C_{D_7} = 0.140$$

C_{D_8}:

C_{D_8} = 0 (rear wheel wells not covered)

C_{D_8} = -0.01 (rear wheel well covered)

C_{D_8} = 0.0

C_{D_9}:

A_{p_1}(mirror) 0.1591 A_{p_3} ______ A_R 24.137

A_{p_2} ______ A_{p_4} ______

$$C_{D_9} = \frac{1.1}{A_R} \sum A_{p_j}$$

$$C_{D_9} = 0.0073$$

$C_{D_{10}}$:

A_M 0 A_R 0

$$C_{D_{10}} = \frac{0.4\, A_M}{A_R}$$

$$C_{D_{10}} = 0.0$$

$C_{D_{11}}$:

$$k = 1.146\ (m/sec)^{-2}$$

$$= 0.229\ (mph)^{-2}$$

$$\left(u_r/u\right) = 0.233\ \left[1.0 - k\ (u/100)^2\right]$$

A_r (= $L_r \times h_r$) 3.438 ft^2, A_R 24.137 ft^2

Sample Calculation (Continued)

$\underline{C_{D_{11}}}$ (Cont'd)

$$C_{D_{11}} = 1.8 \left(\frac{A_r}{A_R}\right)\left(\frac{u_r}{u}\right)\left[1.0 - 0.75\left(\frac{u_r}{u}\right)\right] = 0.3303 \left(\frac{A_r}{A_R}\right) \text{ @ 50 mph}$$

$$C_{D_{11}} = 0.0470$$

$\underline{C_D}$:

$$C_D = \sum C_{D_1} = 0.5618$$

APPENDIX C

VEHICLE DIMENSIONS AND AREAS

The individual vehicle dimensions and areas which are required to evaluate the aerodynamic drag coefficient according to the methods outlined in Appendix A are given for each of the 20 vehicles evaluated.

When more than one edge radius is indicated for a given portion of the vehicle, the effective value was determined as follows:

$$R = \frac{\Sigma RiEi}{\Sigma Ei}$$

where

R = effective edge radius

Ri = specific radius over length Ei

Ei = projected length associated with a given radius, Ri

The parameter (R/E) was then taken to be the ratio of the effective edge radius to the sum of the individual edge lengths, Ei.

VEHICLE DIMENSIONS/AREAS

Vehicle:

Manufacturer	Chrysler
Make	Plymouth Arrow
Model	2-dr. Coupe
Model Year	1977
License No/VIN	Dlr 2529 (Calif.)/7P24K78901899

Projected Frontal Area, ft^2 17.82

C_{D_1}: Front End Drag Coefficient

Location						
1. hood portion	R_{u_1}	0.125 in.	E_{u_1}	46.59 in.	$(R/E)_u$	0.0027
2. above headlights	R_{u_2}	0.25 in.	E_{u_2}	4.24 in.		
1. body sheet metal below bumper	R_{ℓ_1}	0.125 in.	E_{ℓ_1}	51.45 in.	$(R/E)_\ell$	0.0024
1. upper portion of fender	R_{v_1}	0.375 in.	E_{v_1}	6 in.	$(R/E)_v$	0.0625
2. lower portion of fender	R_{v_2}	1 in.	E_{v_2}	2.5 in.		
3. upper portion of bumper and lower sheetmetal	R_{v_3}	1.625 in.	E_{v_3}	4.5 in.		
4. lower portion of bumper	R_{v_4}	1.313 in.	E_{v_4}	3 in.		
					A_F	6.985 ft^2

C_{D_2}: Windshield Drag Coefficient

Location						
1. roof windshield intersection	$R_{u'}$	4.5 in.	$E_{u'}$	39.76 in.	$(R/E)_{u'}$	0.113*
2. A-post	$R_{v'}$	3 in.	$E_{v'}$	13.25 in.	$(R/E)_{v'}$	0.226*
3. windshield slope from vertical	γ	60°	A_W	3.773 ft^2		*exceeds max. use 0.105

Vehicle: 1977 Plymouth Arrow (Continued)

C_{D_3} : Front Hood Drag Coefficient

Location		
1. front area below windshield	A_h	9.413 ft^2
2. front end area	A_F	6.985 ft^2
3. hood length	L_h	4.028 ft

C_{D_4} : Rear Vertical Edge Drag Coefficient

Location						
1. upper portion of vertical section	R_{v_1} 0.875 in.	E_{b_1} 10.5 in.	R_v 1.030 in.
2. lower portion of vertical section	R_{v_2} 1 in.	E_{b_2} 3 in.	E_b 18.75 in.
3. upper portion of bumper	R_{v_3} 1.5 in.	E_{b_3} 2.25 in.	W 57.50 in.
4. lower portion of bumper	R_{v_4} 1.25 in.	E_{b_4} 3 in.	H 37.07 in.

C_{D_5} : Base Region Drag Coefficient

Location			
1. area of base region	A_B 7.845 ft^2	
2. area of hatch portion	A_H 4.267 ft^2	
3. rear slope from horizontal	ϕ 19°	C_{D_H}/C_{D_B} 0.860

C_{D_6} : Underbody Drag Coefficient

Location		
1. underbody length	L 12.566 ft	
2. underbody width	W 4.242 ft	A_p(= LXW) 53.30 ft^2

Vehicle: 1977 Plymouth Arrow (Continued)

C_{D_9} : Protuberance Drag Coefficient

Location

1. antenna A_{p_1} 0.0609 ft^2 ΣA_{p_j} 0.0609 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. one each side A_M 0.323 ft^2

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 12.125 in.

radiator width 18.375 in. A_r 1.547 ft^2

Vehicle:	Manufacturer	Chrysler
	Make	Plymouth Volare
	Model	Station Wagon
	Model Year	1977
	License No/VIN	Dlr 2529 (Calif.)/HH45G7G135783

Projected Frontal Area, ft^2 22.76

C_{D_1} : Front End Drag Coefficient

Location						
1. above headlights	R_{u_1}	0.125 in.	E_{u_1}	20 in.	$(R/E)_u$	0.0092
2. above parking lights	R_{u_2}	2 in.	E_{u_2}	16.94 in.		
3. above grille	R_{u_3}	0.0625 in.	E_{u_3}	27.23 in.		
1. botton of bumper	R_{ℓ_1}	1.75 in.	E_{ℓ_1}	66.30 in.	$(R/E)_\ell$	0.0264
1. at fender	R_{v_1}	0.563 in.	E_{v_1}	9 in.	$(R/E)_v$	0.0974
2. upper portion of bumper	R_{v_2}	3.75 in.	E_{v_2}	2.75 in.		
3. lower portion of bumper	R_{v_3}	2.25 in.	E_{v_3}	4.25 in.		
					A_F	8.861 ft^2

C_{D_2} : Windshield Drag Coefficient

Location						
1. roof-windshield intersection	$R_{u'}$	1.625 in.	$E_{u'}$	49.03 in.	$(R/E)_{u'}$	0.0331
2. A-post	$R_{v'}$	1.125 in.	$E_{v'}$	16.24 in.	$(R/E)_{v'}$	0.0693
3. windshield slope from vertical	γ	51°	A_W	5.888 ft^2		

Vehicle: 1977 Volare Station Wagon (Continued)

C_{D_3} : Front Hood Drag Coefficient

Location

1. front area below windshield — A_h 11.783 ft^2
2. front end area — A_F 8.861 ft^2
3. hood length — L_h 4.508 ft

C_{D_4} : Rear Vertical Edge Drag Coefficient

Location			
1. vertical portion above bumper	R_{v_1} 0.688 in.	E_{b_1} 7 in.	R_v 0.996 in.
2. upper portion of bumper	R_{v_2} 1.875 in.	E_{b_2} 2 in.	E_b 15 in.
3. lower portion of bumper	R_{v_3} 1.063 in.	E_{b_3} 6 in.	W 65.87 in.
			H 42.17 in.

C_{D_5} : Base Region Drag Coefficient

Location

1. area of base region — A_B 7.360 ft^2
2. area of hatch portion — A_H 9.530 ft^2
3. rear slope from horizontal — ϕ 45° — C_{D_H}/C_{D_B} 1.0

C_{D_6} : Underbody Drag Coefficient

Location

1. underbody length — L 16.507 ft
2. underbody width — W 4.854 ft — A_p(= LXW) 80.13 ft^2

Vehicle: 1977 Volare Station Wagon (Continued)

C_{D_9}: Protuberance Drag Coefficient

Location

1. mirrors (one each side) A_{p_1} $0.2417\ ft^2$

2. antenna A_{p_2} $0.0260\ ft^2$

3. luggage rack A_{p_3} $0.1828\ ft^2$ ΣA_{p_j} $0.4505\ ft^2$

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 17.25 in.

radiator width 26.25 in. A_r $3.145\ ft^2$

Vehicle: Manufacturer Chrysler
Make LeBaron
Model 4-dr. Sedan
Model Year 1978
License No/VIN 311 TYY (Calif.)/FP41J8G145760

Projected Frontal Area, ft^2 23.05

C_{D_1}: Front End Drag Coefficient

Location		R		E		R/E	
1. above headlights	R_{u_1}	1.5 in.	E_{u_1}	30.78 in.	$(R/E)_u$	0.0122
2. above grille	R_{u_2}	0.031 in.	E_{u_2}	31.38 in.		
1. center segment of bumper	R_{ℓ_1}	2.75 in.	E_{ℓ_1}	31.03 in.	$(R/E)_\ell$	0.0318
2. outer segments of bumper	R_{ℓ_2}	1.563 in.	E_{ℓ_2}	35.51 in.		
1. headlight trim, horizontal portion	R_{v_1}	0.75 in.	E_{v_1}	1.5 in.	$(R/E)_v$	0.0618
2. fender above headlights	R_{v_2}	0.469 in.	E_{v_2}	2 in.		
3. headlight trim, vertical portion	R_{v_3}	0.031 in.	E_{v_3}	7.5 in.		
4. bumper	R_{v_4}	2.625 in.	E_{v_4}	5.5 in.		

A_F 8.991 ft^2

C_{D_2}: Windshield Drag Coefficient

(Location)

1. roof-windshield intersection	$R_{u'}$	2.625 in.	$E_{u'}$	47.90 in.	$(R/E)_{u'}$	0.0548
2. A-post	$R_{v'}$	1.125 in.	$E_{v'}$	16.04 in.	$(R/E)_{v'}$	0.0701
3. windshield slope from vertical	γ	51.5°	A_W	5.869 ft^2		

Vehicle: 1978 Le Baron (Continued)

C_{D_3}: Front Hood Drag Coefficient

Location

1. front area below windshield — A_h 11.500 ft^2
2. front end area — A_F 8.991 ft^2
3. hood length — L_h 4.766 ft

C_{D_4}: Rear Vertical Edge Drag Coefficient

Location				
1. vertical portion of body	R_{v_1} 1.375 in.	E_{b_1} 8 in.	R_v 1.394 in.
2. sloping portion of body	R_{v_2} 1.281 in.	E_{b_2} 3 in.	E_b 18.5 in.
3. upper portion of bumper	R_{v_3} 1.875 in.	E_{b_3} 2.5 in.	W 66.97 in.
4. lower portion of bumper	R_{v_4} 1.25 in.	E_{b_4} 5 in.	H 42.51 in.

C_{D_5}: Base Region Drag Coefficient

Location

1. area of base region — A_B 8.770 ft^2
2. area of hatch portion — A_H 7.866 ft^2
3. rear slope from horizontal — ϕ 22° — C_{D_H}/C_{D_B} 1.06

C_{D_6}: Underbody Drag Coefficient

Location

1. underbody length — L 16.801 ft
2. underbody width — W 4.818 ft — A_p(= LXW) 80.94 ft^2

Vehicle: 1978 Le Baron (Continued)

C_{D_9} : Protuberance Drag Coefficient

Location

1. mirrors (one each side) A_{p_1} 0.2475 ft^2
2. antenna A_{p_2} 0.0394 ft^2
3. hood ornament A_{p_3} 0.0104 ft^2 ΣA_{p_j} 0.2973 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 17 in.

radiator width 25.5 in. A_r 3.0104 ft^2

Vehicle:	Manufacturer	Chrysler
	Make	Plymouth Volare
	Model	Station Wagon
	Model Year	1978
	License No/VIN	Dlr 2529 (Calif.)/HL45C8B170977

Projected Frontal Area, ft^2 22.79

C_{D_1} : Front End Drag Coefficient

Location							
1.	above headlights	R_{u_1}	0.125 in.	E_{u_1}	19.48 in.	$(R/E)_u$	0.0075
2.	above parking lights	R_{u_2}	1.5 in.	E_{u_2}	18.10 in.		
3.	above grille	R_{u_3}	0.0625 in.	E_{u_3}	26.97 in.		
1.	bottom of bumper	R_{ℓ_1}	1.375 in.	E_{ℓ_1}	66.76 in.	$(R/E)_\ell$	0.0206
1.	at headlights	R_{v_1}	0.438 in.	E_{v_1}	9 in.	$(R/E)_v$	0.0871
2.	upper portion of bumper	R_{v_2}	3.25 in.	E_{v_2}	2.75 in.		
3.	lower portion of bumper	R_{v_3}	2.25 in.	E_{v_3}	4.5 in.		
						A_F	8.727 ft^2

C_{D_2} : Windshield Drag Coefficient

Location							
1.	roof-windshield intersection	$R_{u'}$	2.5 in.	$E_{u'}$	48.27 in.	$(R/E)_{u'}$	0.0518
2.	A-post	$R_{v'}$	1 in.	$E_{v'}$	17.64 in.	$(R/E)_{v'}$	0.0567
3.	windshield slope from horizontal	γ	51°	A_W	5.906 ft^2		

Vehicle 1978 Volare Station Wagon (Continued)

C_{D_3} : Front Hood Drag Coefficient

Location

1. front area below windshield — A_h 11.622 ft^2
2. front end area — A_F 8.727 ft^2
3. hood length — L_h 4.537 ft

C_{D_4} : Rear Vertical Edge Drag Coefficient

Location				
1. vertical portion above bumper	R_{v_1} 0.688 in.	E_{b_1} 7 in.	R_v 0.978 in.
2. upper portion of bumper	R_{v_2} 1.625 in.	E_{b_2} 2 in.	E_b 14 in.
3. lower portion of bumper	R_{v_3} 1.125 in.	E_{b_3} 5 in.	W 65.56 in.
			H 40.50 in.

C_{D_5} : Base Region Drag Coefficient

Location

1. area of base region — A_B 6.859 ft^2
2. area of hatch portion — A_H 9.476 ft^2
3. rear slope from horizontal — ϕ 45° — C_{D_H}/C_{D_B} 1.0

C_{D_6} : Underbody Drag Coefficient

Location

1. underbody length — L 16.462 ft
2. underbody width — W 4.882 ft — A_p(= LXW) 80.36 ft^2

Vehicle: 1978 Volare Station Wagon (Continued)

C_{D_9} : Protuberance Drag Coefficient

Location

1. mirrors (one each side) A_{p_1} 0.2570 ft^2
2. antenna A_{p_2} 0.0267 ft^2
3. luggage rack A_{p_3} 0.1828 ft^2 ΣA_{p_j} 0.4665 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 18.75 in.

radiator width 22.0 in. A_r 2.865 ft^2

Vehicle: Manufacturer Ford
Make Granada
Model 4-dr. Sedan
Model Year 1977
License No/VIN 132 RTT(Calif.)/7W81F121893

Projected Frontal Area, ft^2 22.22

C_{D_1} : Front End Drag Coefficient

Location						
1. at fender	R_{u_1}	1.875 in.	E_{u_1}	1.25 in.	$(R/E)_u$	0.0198
2. above headlights	R_{u_2}	2.625 in.	E_{u_2}	28 in.		
3. above grille	R_{u_3}	0.0625 in.	E_{u_3}	33.5 in.		
1. bottom of bumper	R_{ℓ_1}	1.125 in.	E_{ℓ_1}	62.61 in.	$(R/E)_\ell$	0.0180
1. at fender	R_{v_1}	0.125 in.	E_{v_1}	12 in.	$(R/E)_v$	0.0478
2. at bumper	R_{v_2}	2.25 in.	E_{v_2}	7 in.		
					A_F	8.943 ft^2

C_{D_2} : Windshield Drag Coefficient

Location						
1. roof-windshield intersection	$R_{u'}$	4.5 in.	$E_{u'}$	47.62 in.	$(R/E)_{u'}$	0.0945
2. A-post	$R_{v'}$	1.625 in.	$E_{v'}$	14.87 in.	$(R/E)_{v'}$	0.109*
3. windshield slope from vertical	γ	56°	A_W	5.312 ft^2	*exceeds max. use 0.105	

Vehicle: 1977 Ford Granada (Continued)

C_{D_3}: Front Hood Drag Coefficient

Location

1. front area below windshield — A_h 11.033 ft^2
2. front end area — A_F 8.943 ft^2
3. hood length — L_h 4.648 ft

C_{D_4}: Rear Vertical Edge Drag Coefficient

Location				
1. vertical portion above tail light	R_{v_1} 1.125 in.	E_{b_1} 1.75 in.	R_v 1.576 in.
2. tail light portion	R_{v_2} 0.6875 in.	E_{b_2} 4.5 in.	E_b 21.51 in.
3. vertical portion below tail light	R_{v_3} 1.0 in.	E_{b_3} 2.5 in.	W 64.60 in.
4. sloping portion above tail light	R_{v_4} 0.906 in.	E_{b_4} 5.26 in.	H 38.21 in.
5. bumper	R_{v_5} 2.875 in.	E_{b_5} 7.5 in.	

C_{D_5}: Base Region Drag Coefficient

Location

1. area of base region — A_B 10.00 ft^2
2. area of hatch portion — A_H 6.24 ft^2
3. rear slope from horizontal — ϕ 20° — C_{D_H}/C_{D_B} 0.925

C_{D_6}: Underbody Drag Coefficient

Location

1. underbody length — L 16.281 ft
2. underbody width — W 4.814 ft — A_p(= LXW) 78.38 ft^2

Vehicle: 1977 Ford Granada (Continued)

C_{D_9}: Protuberance Drag Coefficient

Location

1. mirror A_{p_1} 0.1212 ft^2
2. antenna A_{p_2} 0.0269 ft^2
3. hood ornament A_{p_3} 0.0113 ft^2 ΣA_{p_j} 0.1594 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 18 in.

radiator width 26.5 in. A_r 3.313 ft^2

Vehicle:

Manufacturer	Ford
Make	LTD II
Model	4-dr. Sedan
Model Year	1977
License No/VIN	404 SYY (Calif.)/7A31H156239

Projected Frontal Area, ft^2 23.22

C_{D_1} : Front End Drag Coefficient

Location						
1. at fender	R_{u_1}	1.375 in.	E_{u_1}	20 in.	$(R/E)_u$	0.0090
2. above headlights	R_{u_2}	0.563 in.	E_{u_2}	17 in.		
3. above grille	R_{u_3}	0.0625 in.	E_{u_3}	28.9 in.		
1. bottom of bumper	R_{ℓ_1}	0.50 in.	E_{ℓ_1}	67.5 in.	$(R/E)_\ell$	0.0074
1. at fender	R_{v_1}	0.0625 in. (use 0)	E_{v_1}	12.5 in.	$(R/E)_v$	0.0322
2. bumper	R_{v_2}	1.75 in.	E_{v_2}	7 in.		
					A_F	9.024 ft^2

C_{D_2} : Windshield Drag Coefficient

Location						
1. roof-windshield intersection	$R_{u'}$	4.75 in.	$E_{u'}$	46.57 in.	$(R/E)_{u'}$	0.1020
2. A-post	$R_{v'}$	1.125 in.	$E_{v'}$	13.45 in.	$(R/E)_{v'}$	0.0836
3. windshield slope from vertical	γ	59^o	A_W	4.993 ft^2		

Vehicle: 1977 Ford LTD II (Continued)

C_{D_3} : Front Hood Drag Coefficient

Location

1. front area below windshield — A_h 11.375 ft^2
2. front end area — A_F 9.024 ft^2
3. hood length — L_h 5.407 ft

C_{D_4} : Rear Vertical Edge Drag Coefficient

Location				
1. fender	R_{v_1} 0.0625 in.	E_{b_1} 14.95 in.	R_v 1.079 in.
2. bumper	R_{v_2} 3.25 in.	E_{b_2} 7 in.	E_b 21.95 in.
			W 65.51 in.
			H 40.52 in.

C_{D_5} : Base Region Drag Coefficient

Location

1. area of base region — A_B 10.174 ft^2
2. area of hatch portion — A_H 6.040 ft^2
3. rear slope — ϕ 19^o — C_{D_H}/C_{D_B} 0.860

C_{D_6} : Underbody Drag Coefficient

Location

1. underbody length — L 16.242 ft
2. underbody width — W 5.113 ft — A_p(= LXW) 83.05 ft^2

Vehicle: 1977 Ford LTD II (Continued)

C_{D_9}: Protuberance Drag Coefficient

Location

1. mirror — A_{P_1} 0.1153 ft^2
2. antenna — A_{P_2} 0.0269 ft^2
3. hood ornament — A_{P_3} 0.0247 ft^2 — ΣA_{P_j} 0.1669 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none — A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 19.5 in.

radiator width 28 in. — A_r 3.792 ft^2

Vehicle: Manufacturer: Ford
Make: Mustang II
Model: 2-dr. Coupe (Notchback)
Model Year: 1977
License No/VIN: 397 SYY (Calif.)/7R02Z131023

Projected Frontal Area, ft^2: 19.29

C_{D_1} : Front End Drag Coefficient

Location		R		E		
1. above headlights	R_{u_1}	0.031 in.	E_{u_1}	14 in.	$(R/E)_u$	0.0053
2. above grille	R_{u_2}	0.0625 in.	E_{u_2}	33.75 in.		
3. between headlights and grille	R_{u_3}	1.75 in.	E_{u_3}	8 in.		
1. bottom of bumper	R_{ℓ_1}	0.625 in.	E_{ℓ_1}	58 in.	$(R/E)_\ell$	0.0108
1. at headlights	R_{v_1}	0.031 in.	E_{v_1}	8.25 in.	$(R/E)_v$	0.0733
2. upper portion of bumper	R_{v_2}	2.5 in.	E_{v_2}	3 in.		
3. lower portion of bumper	R_{v_3}	2.375 in.	E_{v_3}	3 in.	A_F	6.425 ft^2

C_{D_2} : Windshield Drag Coefficient

Location						
1. roof-windshield intersection	$R_{u'}$	6 in.	$E_{u'}$	41.69 in.	$(R/E)_{u'}$	.0144*
2. A-post	$R_{v'}$	1.75 in.	$E_{v'}$	12.35 in.	$(R/E)_{v'}$	.0142*
3. windshield slope from vertical	γ	59^o	A_W	4.228 ft^2		

*both exceed max. use 0.105 for each

Vehicle: 1977 Ford Mustang II (Continued)

C_{D_3} : Front Hood Drag Coefficient

Location

1. front area below windshield — A_h 8.843 ft²
2. front end area — A_F 6.425 ft²
3. hood length — L_h 4.416 ft

C_{D_4} : Rear Vertical Edge Drag Coefficient

Location				
1. vertical portion of body	R_{v_1} 0.50 in.	E_{b_1} 5 in.	R_v 1.096 in.
2. sloping portion of body	R_{v_2} 0.625 in.	E_{b_2} 5 in.	E_b 17 in.
3. upper portion of bumper	R_{v_3} 2 in.	E_{b_3} 3 in.	W 62.85 in.
4. lower portion of bumper	R_{v_4} 1.75 in.	E_{b_4} 4 in.	H 36.90 in.

C_{D_5} : Base Region Drag Coefficient

Location

1. area of base region — A_B 7.747 ft²
2. area of hatch portion — A_H 5.678 ft²
3. rear slope from horizontal — ϕ 24° — C_{D_H}/C_{D_B} 1.21

C_{D_6} : Underbody Drag Coefficient

Location

1. underbody length — L 14.477 ft
2. underbody width — W 4.550 ft — A_p(= LXW) 65.87 ft²

Vehicle: 1977 Ford Mustang II (Continued)

C_{D_9}: Protuberance Drag Coefficient

Location

1. mirror A_{p_1} 0.1017 ft^2

2. antenna A_{p_2} 0.0250 ft^2 ΣA_{p_j} 0.1267

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 16 in.

radiator width 19 in. A_r 2.111 ft^2

Vehicle:

Manufacturer	Ford
Make	Pinto
Model	3-dr. Runabout
Model Year	1977
License No/VIN	152 TDB (Calif.)/8R11Y105096

Projected Frontal Area, ft^2 19.46

C_{D_1} : Front End Drag Coefficient

Location						
1. above grille	R_{u_1}	6 in.	E_{u_1}	41.5 in.	$(R/E)_u$	0.0707
2. above headlights	R_{u_2}	0.0625 in.	E_{u_2}	18 in.		
1. bottom of bumper	R_{ℓ_1}	0.625 in.	E_{ℓ_1}	61 in.	$(R/E)_\ell$	0.0102
1. at headlights	R_{v_1}	0.0625 in.	E_{v_1}	9 in.	$(R/E)_v$	0.0736
2. upper portion of bumper	R_{v_2}	3 in.	E_{v_2}	2 in.		
3. lower portion of bumper	R_{v_3}	2.5 in.	E_{v_3}	4 in.		
					A_F	6.741 ft^2

C_{D_2} : Windshield Drag Coefficient

Location						
1. roof-windshield intersection	$R_{u'}$	4 in.	$E_{u'}$	36.87 in.	$(R/E)_{u'}$	0.109 in.*
2. A-post	$R_{v'}$	0.375 in.	$E_{v'}$	12.19 in.	$(R/E)_{v'}$	0.031 in.
3. windshield slope from vertical		60°	A_W	4.091 ft^2		*exceeds max. use 0.105

Vehicle: 1977 Ford Pinto (Continued)

C_{D_3} : Front Hood Drag Coefficient

Location

1. front area below windshield — A_h 9.690 ft^2
2. front end area — A_F 6.741 ft^2
3. hood length — L_h 3.819 ft

C_{D_4} : Rear Vertical Edge Drag Coefficient

Location			
1. body portion	R_{v_1} 1.188 in.	E_{b_1} 10 in.	R_v 1.693 in.
2. upper portion of bumper	R_{v_2} 3.25 in.	E_{b_2} 2 in.	E_b 16.5 in.
3. lower portion of bumper	R_{v_3} 2.125 in.	E_{b_3} 4.5 in.	W 60.73 in.
			H 37.05 in.

C_{D_5} : Base Region Drag Coefficient

Location

1. area of base region — A_B 6.629 ft^2
2. area of hatch portion — A_H 6.615 ft^2
3. rear slope from horizontal — ϕ 27° — C_{D_H}/C_{D_B} 1.42

C_{D_6} : Underbody Drag Coefficient

Location

1. underbody length — L 13.964 ft
2. underbody width — W 4.473 ft — A_p(= LXW) 62.46 ft^2

Vehicle: 1977 Ford Pinto (Continued)

C_{D_9} : Protuberance Drag Coefficient

Location

1. mirror — A_{p_1} 0.1037 ft^2
2. antenna — A_{p_2} 0.0250 ft^2 — ΣA_{p_j} 0.1287

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none — A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 16.75 in.

radiator width 17.125 in. — A_r 1.992 ft^2

Vehicle:	Manufacturer	Ford
	Make	Fairmont
	Model	4-dr. Sedan
	Model Year	1978
	License No/VIN	031 UDH (Calif.)/8K92T132207

Projected Frontal Area, ft^2 21.05 ft^2

C_{D_1} : Front End Drag Coefficient

Location				
1. above grille	R_{u_1} 2.25 in.	E_{u_1} 32.41 in.	$(R/E)_u$ 0.0229	
2. above headlights	R_{u_2} 0.375 in.	E_{u_2} 27.87 in.		
1. bottom of bumper	R_{ℓ_1} 0.50 in.	E_{ℓ_1} 63.17 in.	$(R/E)_\ell$ 0.0079	
1. at fender	R_{v_1} 1.125 in.	E_{v_1} 8 in.	$(R/E)_v$ 0.0955	
2. upper portion of bumper	R_{v_2} 2.75 in.	E_{v_2} 2.5 in.		
3. lower portion of bumper	R_{v_3} 2.125 in.	E_{v_3} 3 in.		A_F 7.608 ft^2

C_{D_2} : Windshield Drag Coefficient

Location			
1. roof-windshield intersection	$R_{u'}$ 3.5 in.	$E_{u'}$ 46.0 in.	$(R/E)_{u'}$ 0.0761
2. A-post	$R_{v'}$ 2.25 in.	$E_{v'}$ 17.11 in.	$(R/E)_{v'}$ 0.132*
3. windshield slope from vertical	γ 54°	A_W 5.668 ft^2	*exceeds max. use 0.105

Vehicle: 1978 Ford Fairmont (Continued)

C_{D_3}: Front Hood Drag Coefficient

Location		
1. front area below windshield	A_h	9.828 ft^2
2. front end area	A_F	7.608 ft^2
3. hood length	L_h	4.352 ft

C_{D_4}: Rear Vertical Edge Drag Coefficient

Location						
1. vertical portion of base region	R_{v_1}	1.375 in.	E_{b_1}	4.203 in.	R_v	1.557 in.
2. sloping portion of base region	R_{v_2}	1.313 in.	E_{b_2}	10.088 in.	E_b	20.175 in.
3. upper portion of bumper	R_{v_3}	2.75 in.	E_{b_3}	2.942 in.	W	63.47 in.
4. lower portion of bumper	R_{v_4}	2 in.	E_{b_4}	2.942 in.	H	40.53 in.

C_{D_5}: Base Region Drag Coefficient

Location				
1. area of base region	A_B	9.181 ft^2		
2. area of hatch portion	A_H	6.713 ft^2		
3. rear slope from horizontal	ϕ	20°	C_{D_H}/C_{D_B}	0.925

C_{D_6}: Underbody Drag Coefficient

Location				
1. underbody length	L	15.492 ft		
2. underbody width	W	4.558 ft	A_p(= LXW)	70.62 ft^2

Vehicle: 1978 Ford Fairmont (Continued)

C_{D_9} : Protuberance Drag Coefficient

Location

1. mirror A_{p_1} 0.1383 ft^2

2. antenna A_{p_2} 0.0252 ft^2 ΣA_{p_j} 0.1635 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 19 in.

radiator width 25 in. A_r 3.299 ft^2

Vehicle:	Manufacturer	Ford
	Make	Granada
	Model	4-dr. Sedan
	Model Year	1978
	License No/VIN	492 TSP (Calif.)/8W82F108082

Projected Frontal Area, ft^2 22.18

C_{D_1} : Front End Drag Coefficient

Location		R		E		R/E	
1. fender and body excluding head-lights & grille areas	R_{u_1}	1.75 in.	E_{u_1}	11.75 in.	$(R/E)_u$	0.0066
2. above headlights	R_{u_2}	0.1875 in.	E_{u_2}	20 in.		
3. above grille	R_{u_3}	0.0625 in.	E_{u_3}	31.5 in.		
1. bottom of bumper	R_{ℓ_1}	1.125 in.	E_{ℓ_1}	63.25 in.	$(R/E)_\ell$	0.0178
1. at fender	R_{v_1}	0.125 in. (use 0)	E_{v_1}	11 in.	$(R/E)_v$	0.0392
2. upper portion of bumper	R_{v_2}	2.25 in.	E_{v_2}	3 in.		
3. lower portion of bumper	R_{v_3}	1.5 in.	E_{v_3}	3.5 in.	A_F	8.529 ft^2

C_{D_2} : Windshield Drag Coefficient

Location						
1. roof-windshield intersection	$R_{u'}$	4.75 in.	$E_{u'}$	47.93 in.	$(R/E)_{u'}$	0.0991
2. A-post	$R_{v'}$	1.25 in.	$E_{v'}$	14.26 in.	$(R/E)_{v'}$	0.0877
3. windshield slope from vertical	γ	56°	A_W	5.252 ft^2		

Vehicle: 1978 Ford Granada (Continued)

C_{D_3} : Front Hood Drag Coefficient

Location		
1. front area below windshield	A_h	10.724 ft^2
2. front end area	A_F	8.529 ft^2
3. hood length	L_h	4.719 ft

C_{D_4} : Rear Vertical Edge Drag Coefficient

Location						
1. sloping portion of body	R_{v_1}	1 in.	E_{b_1}	6 in.	R_v	1.543 in.
2. vertical portion of body	R_{v_2}	1.375 in.	E_{b_2}	8.5 in.	E_b	22 in.
3. upper portion of bumper	R_{v_3}	2.75 in.	E_{b_3}	4 in.	W	66.85 in.
4. lower portion of bumper	R_{v_4}	1.5 in.	E_{b_4}	3.5 in.	H	41.0 in.

C_{D_5} : Base Region Drag Coefficient

Location				
1. area of base region	A_B	10.151 ft^2		
2. area of hatch portion	A_H	6.706 ft^2		
3. rear slope from horizontal	ϕ	21°	C_{D_H}/C_{D_B}	1.0

C_{D_6} : Underbody Drag Coefficient

Location				
1. underbody length	L	16.201 ft		
2. underbody width	W	4.672 ft	A_p(= LXW)	75.68 ft^2

Vehicle: 1978 Ford Granada (Continued)

C_{D_9}: Protuberance Drag Coefficient

Location

1. antenna A_{p_1} 0.0530 ft^2 ΣA_{p_j} 0.0530 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. one each side A_M 0.2277 ft^2

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 16.5 in.

radiator width 24 in. A_r 2.750 ft^2

Vehicle:	Manufacturer	Ford
	Make	LTD II
	Model	4-dr. Sedan
	Model Year	1978
	License No/VIN	Dlr 6985 (Calif.)/8A30S175412

Projected Frontal Area, ft^2 23.23

C_{D_1} : Front End Drag Coefficient

Location						
1. fender and body exluding headlights and grille areas	R_{u_1}	1.25 in.	E_{u_1}	20 in.	$(R/E)_u$	0.0082
2. above headlights	R_{u_2}	0.5625 in.	E_{u_2}	17 in.		
3. above grille	R_{u_3}	0.031 in.	E_{u_3}	28.9 in.		
1. bottom of bumper	R_{ℓ_1}	0.625 in.	E_{ℓ_1}	68.5 in.	$(R/E)_\ell$	0.0091
1. at fender	R_{v_1}	0.0625 in. (use 0)	E_{v_1}	12.5 in.	$(R/E)_v$	0.0345
2. upper portion of bumper	R_{v_2}	1.813 in.	E_{v_2}	3 in.		
3. lower portion	R_{v_3}	2 in.	E_{v_3}	3.5 in.		

C_{D_2} : Windshield Drag Coefficient

Location						
1. roof-windshield intersection	$R_{u'}$	6 in.	$E_{u'}$	46.26 in.	$(R/E)_{u'}$	0.1297*
2. A-post	$R_{v''}$	1.25 in.	$E_{v'}$	13.65 in.	$(R/E)_{v'}$	0.0916
3. windshield slope from vertical	γ	59°	A_W	4.901 ft^2		*exceeds max. use 0.105

Vehicle: 1978 Ford LTD II (Continued)

C_{D_3} : Front Hood Drag Coefficient

Location		
1. front area below windshield	A_h	11.459 ft^2
2. front end area	A_F	9.309 ft^2
3. hood length	L_h	5.563 ft

C_{D_4} : Rear Vertical Edge Drag Coefficient

Location						
1. at fender	R_{v_1}	0.0625 in.	E_{b_1}	14.85 in.	R_v	0.856 in.
2. upper portion of bumper	R_{v_2}	3.25 in.	E_{b_2}	3.25 in.	E_b	21.60 in.
3. lower portion of bumper	R_{v_3}	2 in.	E_{b_3}	3.5 in.	W	66.01 in.
					H	40.25 in.

C_{D_5} : Base Region Drag Coefficient

Location				
1. area of base region	A_B	10.273 ft^2		
2. area of hatch portion	A_H	6.069 ft^2		
3. rear slope from horizontal	ϕ	18^o	C_{D_H}/C_{D_B}	0.80

C_{D_6} : Underbody Drag Coefficient

Location				
1. underbody length	L	16.971 ft		
2. underbody width	W	5.042 ft	A_p(= LXW)	85.56 ft^2

Vehicle: 1978 Ford LTD II (Continued)

C_{D_9} : Protuberance Drag Coefficient

Location

1. antenna — A_{p_1} 0.0252 ft^2
2. hood ornament — A_{p_2} 0.0247 ft^2 — ΣA_{p_j} 0.0499 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. one each side — A_M 0.2303 ft^2

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 18 in.

radiator width 28 in. — A_r 3.50 ft^2

Vehicle:	Manufacturer	General Motors
	Make	Chevrolet Impala
	Model	4-dr. Sedan
	Model Year	1977
	License No/VIN	807 SMV (Calif.)/1L69U7C147622

Projected Frontal Area, ft^2 24.14

C_{D_1} : Front End Drag Coefficient

Location						
1. hood-front breakline	R_{u_1}	1.625 in.	E_{u_1}	65.45 in.	$(R/E)_u$	0.0248
1. center segment of bumper	R_{ℓ_1}	1.25 in.	E_{ℓ_1}	37.06 in.	$(R/E)_\ell$	0.0137
2. outer segment of bumper	R_{ℓ_2}	0.563 in.	E_{ℓ_2}	31.35 in.		
1. at fender	R_{v_1}	0.125 in.	E_{v_1}	10.74 in.	$(R/E)_v$	0.0580
2. upper section of bumper	R_{v_2}	3 in.	E_{v_2}	4 in.		
3. center section of bumper	R_{v_3}	1.375 in.	E_{v_3}	1.75 in.		
4. lower section of bumper	R_{v_4}	2 in.	E_{v_4}	1.25 in.		
					A_F	9.657 ft^2

C_{D_2} : Windshield Drag Coefficient

Location						
1. roof-windshield intersection	$R_{u'}$	2.5 in.	$E_{u'}$	50.43 in.	$(R/E)_{u'}$	0.0496
2. A-post	$R_{v'}$	1.5 in.	$E_{v'}$	15.28 in.	$(R/E)_{v'}$	0.0982
3. windshield slope from vertical	γ	53^o	A_W	5.517 ft^2		

Vehicle: 1977 Chevrolet Impala (Continued)

C_{D_3}: Front Hood Drag Coefficient

Location

1. front area below windshield — A_h 12.708 ft^2
2. front end area — A_F 9.657 ft^2
3. hood length — L_h 5.118 ft

C_{D_4}: Rear Vertical Edge Drag Coefficient

Location						
1. fender portion	R_{v_1}	0.125 in.	E_{b_1}	10.55 in.	R_v	0.854 in.
2. upper portion of bumper	R_{v_2}	2.875 in.	E_{b_2}	3.25 in.	E_b	17.05 in.
3. center portion of bumper	R_{v_3}	1.375 in.	E_{b_3}	1.75 in.	W	67.08 in.
4. lower portion of bumper	R_{v_4}	1 in.	E_{b_4}	1.5 in.	H	43.10 in.

C_{D_5}: Base Region Drag Coefficient

Location

1. area of base region — A_B 9.157 ft^2
2. area of hatch portion — A_H 8.629 ft^2
3. rear slope from horizontal — ϕ 20° — C_{D_H}/C_{D_B} 0.925

C_{D_6}: Underbody Drag Coefficient

Location

1. underbody length — L 17.625 ft
2. underbody width — W 4.879 ft — A_p(= LXW) 86.00 ft^2

Vehicle: 1977 Chevrolet Impala (Continued)

C_{D_9} : Protuberance Drag Coefficient

Location

1. mirror — A_{p_1} 0.1591 ft^2 — ΣA_{p_j} 0.1591 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none — A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 18 in.

radiator width 27.5 in. — A_r 3.438 ft^2

Vehicle:	Manufacturer	General Motors
	Make	Chevrolet Nova
	Model	4-dr. Sedan
	Model Year	1977
	License No/VIN	125 SZS (Calif.)/1X69D7L146791

Projected Frontal Area, ft^2 22.56

C_{D_1} : Front End Drag Coefficient

Location				
1. above headlights	R_{u_1} 1 in.	E_{u_1} 20.5 in.	$(R/E)_u$ 0.0200
2. above grille	R_{u_2} 1.375 in.	E_{u_2} 42.26 in.	
1. bottom of bumper	R_{ℓ_1} 1.125 in.	E_{ℓ_1} 64.70 in.	$(R/E)_\ell$ 0.0174
1. fender portion	R_{v_1} 1.5 in.	E_{v_1} 11.10 in.	$(R/E)_v$ 0.120* *exceeds max. use 0.105
2. upper portion of bumper	R_{v_2} 4 in.	E_{v_2} 3.5 in.	
3. lower portion of bumper	R_{v_3} 2.5 in.	E_{v_3} 3.5 in.	

A_F 8.393 ft^2

C_{D_2} : Windshield Drag Coefficient

Location			
1. roof-windshield intersection	$R_{u'}$ 6 in.	$E_{u'}$ 45 in	$(R/E)_{u'}$ 0.1333*
2. A-post	$R_{v'}$ 3 in.	$E_{v'}$ 15.563 in.	$(R/E)_{v'}$ 0.1928*
3. windshield slope from vertical	γ 53°	A_W 5.107 ft^2	*exceeds max. use 0.105

Vehicle: 1977 Chevrolet Nova (Continued)

C_{D_3}: Front Hood Drag Coefficient

Location		
1. front area below windshield	A_h	11.225 ft^2
2. front end area	A_F	8.393 ft^2
3. hood length	L_h	4.674

C_{D_4}: Rear Vertical Edge Drag Coefficient

Location						
1. body above bumper	R_{v_1}	0.375 in.	E_{b_1}	11.326 in.	R_v	1.195 in.
2. upper portion of bumper	R_{v_2}	3.5 in.	E_{b_2}	3.5 in.	E_b	18.826 in.
3. lower portion of bumper	R_{v_3}	1.5 in.	E_{b_3}	4 in.	W	62.291 in.
					H	40.556 in.

C_{D_5}: Base Region Drag Coefficient

Location				
1. area of base region	A_B	8.001 ft^2		
2. area of hatch portion	A_H	7.734 ft^2		
3. rear slope from horizontal	ϕ	21°	C_{D_H}/C_{D_B}	1.0

C_{D_6}: Underbody Drag Coefficient

Location				
1. underbody length	L	15.192 ft		
2. underbody width	W	5.083 ft	A_p(= LXW)	77.22 ft^2

Vehicle: 1977 Chevrolet Nova (Continued)

C_{D_9} : Protuberance Drag Coefficient

Location

1. mirror A_{p_1} 0.1169 ft^2 ΣA_{p_j} 0.1169 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 16 in.

radiator width 26 in. A_r 2.889 ft^2

Vehicle:	Manufacturer	General Motors
	Make	Oldsmobile Cutlass Supreme
	Model	2-dr. Coupe
	Model Year	1977
	License No/VIN	866 SMA (Calif.)/3J57R7R209999

Projected Frontal Area, ft^2 22.62

C_{D_1} : Front End Drag Coefficient

Location		R		E		R/E	
1. center portion	R_{u_1}	1.125 in.	E_{u_1}	10.75 in.	$(R/E)_u$	0.0116
2. above headlights	R_{u_2}	1.188 in.	E_{u_2}	32 in.		
3. sheet metal behind grille	R_{u_3}	0.0625 in.	E_{u_3}	24 in.		
1. center portion of bottom of bumper	R_{ℓ_1}	2.25 in.	E_{ℓ_1}	35 in.	$(R/E)_\ell$	0.0296
2. outer segments of bottom of bumper	R_{ℓ_2}	1.625 in.	E_{ℓ_2}	31 in.		
1. at fender	R_{v_1}	0.125 in.	E_{v_1}	9 in.	$(R/E)_v$	0.0740
2. upper portion of bumper	R_{v_2}	3.25 in.	E_{v_2}	3.75 in.		
3. lower portion of bumper	R_{v_3}	2 in.	E_{v_3}	5 in.		
					A_F	8.406 ft^2

C_{D_2} : Windshield Drag Coefficient

Location						
1. roof-windshield intersection	$R_{u'}$	4.75 in.	$E_{u'}$	45.8 in.	$(R/E)_{u'}$	0.1037
2. A-post	$R_{v'}$	0.75 in.	$E_{v'}$	14.1 in.	$(R/E)_{v'}$	0.0532
3. windshield slope from vertical	γ	56°	A_W	4.522 ft^2		

Vehicle: 1977 Oldsmobile Cutlass Supreme (Continued)

C_{D_3} : Front Hood Drag Coefficient

Location		
1. front area below windshield	A_h	12.279 ft^2
2. front end area	A_F	8.406 ft^2
3. hood length	L_h	5.371 ft

C_{D_4} : Rear Vertical Edge Drag Coefficient

Location						
1. body portion	R_{v_1}	0.25 in.	E_{b_1}	9.5 in.	R_v	0.745 in.
2. upper portion of bumper	R_{v_2}	1.563 in.	E_{b_2}	4.5 in.	E_b	18 in.
3. lower portion of bumper	R_{v_3}	1 in.	E_{b_3}	4 in.	W	65.46 in.
					H	39.93 in.

C_{D_5} : Base Region Drag Coefficient

Location				
1. area of base region	A_B	9.021 ft^2		
2. area of hatch portion	A_H	6.991 ft^2		
3. rear slope from horizontal	ϕ	20^o	C_{D_H}/C_{D_B}	0.925

C_{D_6} : Underbody Drag Coefficient

Location				
1. underbody length	L	15.800 ft		
2. underbody width	W	4.970 ft	A_p(= LXW)	78.53 ft^2

Vehicle: 1977 Oldsmobile Cutlass Supreme (Continued)

C_{D_9}: Protuberance Drag Coefficient

Location

1. mirror — A_{p_1} 0.1491 ft^2

2. hood ornament — A_{p_2} 0.0275 ft^2 — ΣA_{p_j} 0.1766 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none — A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 15.5 in.

radiator width 28 in. — A_r 3.014 ft^2

Vehicle:	Manufacturer	General Motors
	Make	Chevrolet Impala
	Model	4-dr. Sedan
	Model Year	1978
	License No/VIN	759 ULU (Calif.)/1L69U8S193433

Projected Frontal Area, ft^2 23.89

C_{D_1}: Front End Drag Coefficient

Location

1. above headlights	R_{u_1}	1.5 in.	E_{u_1}	28.52 in.	$(R/E)_u$	0.0244
2. above grille	R_{u_2}	1.625 in.	E_{u_2}	35.93 in.		
1. center segment of bumper	R_{ℓ_1}	1.5 in.	R_{ℓ_1}	37.28 in.	$(R/E)_\ell$	0.0154
2. outer segment of bumper	R_{ℓ_2}	0.563 in.	R_{ℓ_2}	31.89 in.		
1. at headlights	R_{v_1}	0.125 in.	E_{v_1}	10 in.	$(R/E)_v$	0.0676
2. upper portion of bumper	R_{v_2}	3.25 in.	E_{v_2}	4 in.		
3. center portion of bumper	R_{v_3}	1.5 in.	E_{v_3}	1.75 in.		
4. lower portion of bumper	R_{v_4}	2.125 in.	E_{v_4}	1.25 in.		
					A_F	9.843 ft^2

C_{D_2}: Windshield Drag Coefficient

Location

1. roof-windshield intersection	$R_{u'}$	2.625 in.	$E_{u'}$	50.51 in.	$(R/E)_{u'}$	0.0520
2. A-post	$R_{v'}$	1.375 in.	$E_{v'}$	15.15 in.	$(R/E)_{v'}$	0.0907
3. windshield slope from vertical	γ	53°	A_W	5.482 ft^2		

Vehicle: 1978 Chevrolet Impala (Continued)

C_{D_3}: Front Hood Drag Coefficient

Location

1. front area below windshield — A_h 12.659 ft^2
2. front end area — A_F 9.843 ft^2
3. hood length — L_h 5.067 ft

C_{D_4}: Rear Vertical Edge Drag Coefficient

Location				
1. at fender	R_{v_1} 0.125 in.	E_{b_1} 10.34 in.	R_v 0.997 in.
2. upper portion of bumper	R_{v_2} 3.25 in.	E_{b_2} 3.25 in.	E_b 16.84 in.
3. center portion of bumper	R_{v_3} 1.75 in.	E_{b_3} 1.75 in.	W 67.28 in.
4. lower portion of bumper	R_{v_4} 1.25 in.	E_{b_4} 1.5 in.	H 43.84 in.

C_{D_5}: Base Region Drag Coefficient

Location

1. area of base region — A_B 9.110 ft^2
2. area of hatch portion — A_H 8.710 ft^2

e. rear slope from horizontal — ϕ 20° — C_{D_H}/C_{D_B} 0.925

C_{D_6}: Underbody Drag Coefficient

Location

1. underbody length — L 17.63 ft
2. underbody width — W 5.03 ft — A_p(= LXW) 88.77 ft^2

Vehicle: 1978 Chevrolet Impala (Continued)

C_{D_9} : Protuberance Drag Coefficient

Location

1. mirror A_{p_1} 0.1295 ft^2 ΣA_{p_j} 0.1295 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 18 in.

radiator width 27.5 in. A_r 3.438 ft^2

Vehicle:

Manufacturer	General Motors
Make	Chevrolet Monza
Model	2-dr. Fastback
Model Year	1978
License No/VIN	none (Hessell Chevrolet)/1R07A8U102658

Projected Frontal Area, ft^2 19.04

C_{D_1}: Front End Drag Coefficient

	Location	R		E		R/E	
1.	above headlights	R_{u_1}	0.0625 in.	E_{u_1}	30 in.	$(R/E)_u$	0.0011
2.	between headlights	R_{u_2}	0.0625 in.	E_{u_2}	26 in.		
1.	body below bumper	R_1	0.0625 in.	E_1	53 in.	(R/E)	0.0012
1.	at headlights	R_{v_1}	0.0625 in. (use 0)	E_{v_1}	8.5 in.	$(R/E)_v$	0.0294
2.	bumper	R_{v_2}	2 in.	E_{v_2}	3 in.		
3.	body below bumper	R_{v_3}	0.0625 in.	E_{v_3}	3 in.		

A_F 5.268 ft^2

C_{D_2}: Windshield Drag Coefficient

	Location						
1.	roof-windshield intersection	$R_{u'}$	6 in.	$E_{u'}$	42.98 in.	$(R/E)_{u'}$	0.1396*
2.	A-post	$R_{v'}$	2.5 in.	$E_{v'}$	12.69 in.	$(R/E)_{v'}$	0.197*
3.	windshield slope from vertical	γ	61°	A_W	4.263 ft^2	*exceeds max. use 0.105	

Vehicle: 1978 Chevrolet Monza (Continued)

C_{D_3}: Front Hood Drag Coefficient

Location

1. front area below windshield — A_h 9.026 ft^2
2. front end area — A_F 5.268 ft^2
3. hood length — L_h 4.400 ft

C_{D_4}: Rear Vertical Edge Drag Coefficient

Location						
1. tail light	R_{v_1}	2.25 in.	E_{b_1}	3.5 in.	R_v	3.348 in.
2. bottom of tail light to bottom of bumper	R_{v_2}	2.75 in.	E_{b_2}	6 in.	E_b	14 in.
3. below bumper	R_{v_3}	5 in.	E_{b_3}	4.5 in.	W	53.47 in.
					H	39.18 in.

C_{D_5}: Base Region Drag Coefficient

Location

1. area of base region — A_B 5.535 ft^2
2. area of hatch portion — A_H 5.089 ft^2
3. rear slope from horizontal — ϕ 21° — C_{D_H}/C_{D_B} 1.0

C_{D_6}: Underbody Drag Coefficient

Location

1. underbody length — L 14.056 ft
2. underbody width — W 4.477 ft — A_p(= LXW) 62.92 ft^2

Vehicle: 1978 Chevrolet Monza (Continued)

C_{D_9} : Protuberance Drag Coefficient

Location

1. none — A_{p_1} 0 — ΣA_{p_j} 0

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. one each side — A_M 0.2313 ft^2

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 15 in.

radiator width 20 in. — A_r 2.083 ft^2

Vehicle:	Manufacturer	General Motors
	Make	Chevrolet Nova
	Model	4-dr. Sedan
	Model Year	1978
	License No/VIN	None (Hessell Chevrolet)/1Y69U8102645

Projected Frontal Area, ft^2 22.77

C_{D_1} : Front End Drag Coefficient

Location						
1. hood-front breakline	R_{u_1}	2.125 in.	E_{u_1}	62.44 in.	$(R/E)_u$	0.0340
1. bottom of bumper	R_{ℓ_1}	1.25 in.	E_{ℓ_1}	64.27 in.	$(R/E)_\ell$	0.0194
1. at headlights	R_{v_1}	.031 in. (use 0)	E_{v_1}	7.5 in.	$(R/E)_v$	0.1021
2. above headlights	R_{v_2}	0.0625 in.	E_{v_2}	1.25 in.		
3. upper portion of bumper	R_{v_3}	4.75 in.	E_{v_3}	4 in.		
4. lower portion of bumper	R_{v_4}	2.25 in.	E_{v_4}	3.5 in.		
					A_F	7.967 ft^2

C_{D_2} : Windshield Drag Coefficient

Location						
1. roof-windshield intersection	$R_{u'}$	3.5 in.	$E_{u'}$	45.65 in.	$(R/E)_{u'}$	0.0767
2. A-post	$R_{v'}$	3 in.	$E_{v'}$	15.82 in.	$(R/E)_{v'}$	0.1896*
3. windshield slope from vertical	γ	54°	A_W	5.015 ft^2		*exceeds max. use 0.105

Vehicle: 1978 Chevrolet Nova (Continued)

C_{D_3} : Front Hood Drag Coefficient

Location		
1. front area below windshield	A_h	10.846 ft^2
2. front end area	A_F	7.967 ft^2
3. hood length	L_h	4.721 ft

C_{D_4} : Rear Vertical Edge Drag Coefficient

Location						
1. body above bumper	R_{v_1}	0.938 in.	E_{b_1}	10.338 in.	R_v	1.537 in.
2. upper portion of bumper	R_{v_2}	3.25 in.	E_{b_2}	4 in.	E_b	18.338 in.
3. lower portion of bumper	R_{v_3}	1.375 in.	E_{b_3}	4 in.	W	62.428 in.
					H	41.292 in.

C_{D_5} : Base Region Drag Coefficient

Location				
1. area of base region	A_B	7.842 ft^2		
2. area of hatch portion	A_H	8.039 ft^2		
3. rear slope from horizontal	ϕ	21^o	C_{D_H}/C_{D_B}	1.0

C_{D_6} : Underbody Drag Coefficient

Location				
1. underbody length	L	15.160 ft		
2. underbody width	W	4.957 ft	A_p(=LXW)	75.15 ft^2

Vehicle: 1978 Chevrolet Nova (Continued)

C_{D_9} : Protuberance Drag Coefficient

Location

1. mirror A_{p_1} 0.1468 ft^2 ΣA_{p_j} 0.1468 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 16 in.

radiator width 26 in. A_r 2.889 ft^2

Vehicle:	Manufacturer	General Motors
	Make	Oldsmobile Cutlass Supreme
	Model	2-dr. Coupe
	Model Year	1978
	License No/VIN	448 TRW (Calif.)/3R47F8R407693

Projected Frontal Area, ft^2 21.58

C_{D_1} : Front End Drag Coefficient

Location						
1. hood-front breakline	R_{u_1}	0.0625 in.	E_{u_1}	63.20 in.	$(R/E)_u$	0.0010
1. center segment of bumper	R_{ℓ_1}	0.813 in.	E_{ℓ_1}	15 in.	$(R/E)_\ell$	0.0242
2. outer segment of bumper	R_{ℓ_2}	1.75 in.	E_{ℓ_2}	48 in.		
1. at fender	R_{v_1}	0.625 in.	E_{v_1}	8 in.	$(R/E)_v$	0.0814
2. upper portion of bumper	R_{v_2}	2.375 in.	E_{v_2}	3.5 in.		
3. lower portion of bumper	R_{v_3}	1.563 in.	E_{v_3}	4 in.	A_F	7.692 ft^2

C_{D_2} : Windshield Drag Coefficient

Location						
1. roof-windshield intersection	$R_{u'}$	3.75 in.	$E_{u'}$	46.5 in.	$(R/E)_{u'}$	0.0806
2. A-post	$R_{v'}$	1.938 in.	$E_{v'}$	14.8 in.	$(R/E)_{v'}$	0.1309*
3. windshield slope from vertical	γ	59°	A_W	4.881 ft^2		*exceeds max. use 0.105

Vehicle: 1978 Oldsmobile Cutlass Supreme (Continued)

C_{D_3} : Front Hood Drag Coefficient

Location

1. front area below windshield — A_h 11.286 ft^2
2. front end area — A_F 7.692 ft^2
3. hood length — L_h 4.663 ft

C_{D_4} : Rear Vertical Edge Drag Coefficient

Location			
1. body portion	R_{v_1} 0.0625 in.	E_{b_1} 9.25 in.	R_v 1.086 in.
2. upper portion of bumper	R_{v_2} 3 in.	E_{b_2} 3.5 in.	E_b 16.25 in.
3. lower portion of bumper	R_{v_3} 1.875 in.	E_{b_3} 3.5 in.	W 62.60 in.
			H 41.52 in.

C_{D_5} : Base Region Drag Coefficient

Location

1. area of base region — A_B 8.660 ft^2
2. area of hatch portion — A_H 7.254 ft^2
3. rear slope from horizontal — ϕ 23° — C_{D_H}/C_{D_B} 1.14

C_{D_6} : Underbody Drag Coefficient

Location

1. underbody length — L 15.233 ft
2. underbody width — W 4.716 ft — A_p(= LXW) 71.84 ft^2

Vehicle: 1978 Oldsmobile Cutlass Supreme (Continued)

C_{D_9} : Protuberance Drag Coefficient

Location

1. mirrors (one each side) A_{p_1} $0.2575\ ft^2$

2. hood ornament A_{p_2} $0.0091\ ft^2$ ΣA_{p_j} $0.2666\ ft^2$

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 16 in.

radiator width 28 in. A_r $3.111\ ft^2$

Vehicle:	Manufacturer	Porsche
	Make	Porsche
	Model	924
	Model Year	1978
	License No/VIN	Distr. 11976 (Calif.)

Projected Frontal Area, ft^2 18.88

C_{D_1} : Front End Drag Coefficient

Location						
1. top edge of bumper	R_{u_1}	0.438 in.	E_{u_1}	54.9 in.	$(R/E)_u$	0.0080
1. bottom edge of front dam	R_{ℓ_1}	0.063 in.	E_{ℓ_1}	57.8 in.	$(R/E)_\ell$	0.0011
1. at bumper	R_{v_1}	7.0 in.	E_{v_1}	4.75 in.	$(R/E)_v$	1.474*

*exceeds max. use 0.105

A_F 4.633 ft^2

C_{D_2} : Windshield Drag Coefficient

Location						
1. roof-windshield intersection	$R_{u'}$	12 in.	$E_{u'}$	44.0 in.	$(R/E)_{u'}$	0.273*
2. A-post	$R_{v'}$	4.5 in.	$E_{v'}$	12.9 in.	$(R/E)_{v'}$	0.349*
3. windshield slope from vertical	γ	60°	A_W	4.132 ft^2	*exceeds max. use 0.105	

C_{D_3} : Front Hood Drag Coefficient

Location		
1. area of front below windshield	A_h	10.548 ft^2
2. front end area	A_F	4.633 ft^2
3. hood length	L_h	4.858 ft

Vehicle: 1978 Porsche 924 (Continued)

C_{D_4}: Rear Vertical Edge Drag Coefficient

Location

1. above tail lights R_{v_1} 6 in. E_{b_1} 5.12 in. R_v 5.275 in.
2. below tail lights R_{v_2} 5.5 in. E_{b_2} 5.12 in. E_b 15 in.
3. bumper R_{v_3} 4.25 in. E_{b_3} 4.75 in. W 54.885 in.

H 36.6 in.

C_{D_5}: Base Region Drag Coefficient

Location

1. area of base region A_B 7.198 ft^2
2. area of hatch portion A_H 2.627 ft^2
3. rear slope from horizontal ϕ 17.5° C_{D_H}/C_{D_B} 0.76

C_{D_6}: Underbody Drag Coefficient

Location

1. underbody length L 12.287 ft
2. underbody width W 4.740 ft A_p(= LXW) 58.24 ft^2

C_{D_9}: Protuberance Drag Coefficient

Location

1. mirror A_{p_1} 0.1455 ft^2
2. antenna A_{p_2} 0.0436 ft^2 ΣA_{p_j} 0.1891 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 10.75 in.

radiator width 20.375 in. A_r 1.521 ft^2

Vehicle: Manufacturer Volkswagen
Make Rabbit (Diesel)
Model 2-dr. Hatchback
Model Year 1977
License No/VIN Distr. 11976 (Calif.)/1773260730

Projected Frontal Area, ft^2 19.77

C_{D_1} : Front End Drag Coefficient

Location			
1. hood-front breakline	R_{u_1} 0.375 in.	E_{u_1} 52.1 in.	$(R/E)_u$ 0.0072
1. bottom of front underbody	R_{ℓ_1} 0.031 in.	E_{ℓ_1} 44.3 in.	$(R/E)_\ell$ 0.0007
1. at fender	R_{v_1} 1.75 in.	E_{v_1} 13 in.	$(R/E)_v$ 0.1346*

*exceeds max. use 0.105

A_F 7.188 ft^2

C_{D_2} : Windshield Drag Coefficient

Location			
1. roof-windshield intersection	$R_{u'}$ 5 in.	$E_{u'}$ 42.2 in.	$(R/E)_{u'}$ 0.1185*
2. A-post	$R_{v'}$ 2.25 in.	$E_{v'}$ 15.6 in.	$(R/E)_{v'}$ 0.1449*
3. windshield slope from vertical	γ 51°	A_W 5.415 ft^2	*exceeds max. use 0.105

C_{D_3} : Front Hood Drag Coefficient

Location	
1. area of front below windshield	A_h 10.325 ft^2
2. front end area	A_F 7.188 ft^2
3. hood length	L_h 3.093 ft

Vehicle: 1977 VW Rabbit(Diesel) (Continued)

C_{D_4} : Rear Vertical Edge Drag Coefficient

Location

	Location						
1.	tail light and body above tail light	R_{v_1}	0.25 in.	E_{b_1}	10.25 in.	R_v	1.462 in.
2.	body below tail light	R_{v_2}	2.625 in.	E_{b_2}	3 in.	E_b	18.25 in.
3.	bottom portion of body	R_{v_3}	3.25 in.	E_{b_3}	5 in.	W	50.07 in.
						H	46.35 in.

C_{D_5} : Base Region Drag Coefficient

Location

1. area of base region A_B 8.094 ft^2
2. area of hatch portion A_H 5.331 ft^2
3. rear slope from horizontal ϕ 42° C_{D_H}/C_{D_B} 1.0

C_{D_6} : Underbody Drag Coefficient

Location

1. underbody length L 10.867 ft
2. underbody width W 4.487 ft. A_p(= LXW) 48.76 ft^2

C_{D_9} : Protuberance Drag Coefficient

Location

1. mirror A_{p_1} 0.1226 ft^2
2. antenna A_{p_2} 0.0474 ft^2 ΣA_{p_j} 0.1700 ft^2

$C_{D_{10}}$: Bullet Mirror Drag Coefficient

Location

1. none A_M 0

$C_{D_{11}}$: Cooling Drag Coefficient

radiator height 12 in.

radiator width 18.75 in. A_r 1.562 ft^2

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16. ABSTRACT

This report presents the results of a determination of aerodynamic drag coefficient, C_D, based on an empirical prediction technique developed by The Aerospace Corporation in a previous EPA-sponsored study. This method utilizes an aircraft type "drag build-up" approach wherein the total drag is calculated as the sum of C_D contributions from components of the vehicle. Component contributions are determined from various body/chassis shape parameters. The present study was directed toward the acquisition and application of vehicle measurements data as required to evaluate aerodynamic road load by this prediction method for comparison with measured values.

Twenty 1977/1978 model year passenger cars were examined for which aerodynamic drag coefficients were derived. Comparison of these results with wind tunnel test data on twelve of the vehicles showed good agreement on an average basis; the maximum disparity in an individual result was 18 percent.

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