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ESTIMATION OF VEHICLE AERODYNAMIC DRAG

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Office of Mobile Source Air Pollution Control
Emission Control Technology Division
Ann Arbor, Michigan 48105

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ESTIMATION OF VEHICLE AERODYNAMIC DRAG

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FOREWORD

This report, prepared by The Aerospace Corporation for the U.S. Environmental Protection Agency, Emission Control Technology Division, presents a simple procedure for estimating road vehicle aerodynamic drag using easily quantifiable vehicle shape parameters. The results of a planimeter method for determining vehicle frontal area from photographic enlargements are tabulated and discussed in an appendix. Also presented in appendices are bibliographies on (1) road vehicle aerodynamic drag and procedures for its estimation, and (2) wind tunnel and full-scale testing techniques.

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SUMMARY

A simple procedure was developed for the estimation of road vehicle aerodynamic drag based on easily quantifiable vehicle shape parameters. The procedure is applicable to passenger vehicles, station wagons, and vans and is based on a "drag build-up" method which includes the effects of the basic body shape, underpanning, and cooling drag. Not included are the effects of lift, sidewind, ground clearance, and certain shape details. The limitations of the procedure are discussed and improvements and areas requiring further study are identified. In a related activity, a brief investigation was made of possible techniques for determining vehicle frontal area from photographs of cars. Planimeter measurements of frontal area were made from photographic enlargements of approximately 80 cars. The results of this effort are included as an appendix. Bibliographies on road vehicle aerodynamic drag and on wind tunnel and full-scale road testing techniques are also appended.

SECTION 1

INTRODUCTION AND BACKGROUND

The current method employed by EPA for exhaust emission certification and fuel economy measurement of light-duty vehicles[1*] consists of running the vehicles 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 power settings defined for a discrete set of loaded vehicle weights. Implicit in this procedure is the assumption that the aerodynamic drag correlates with loaded vehicle weight. In reality, the aerodynamic drag of road vehicles is a function of vehicle size and geometry and cannot be adequately correlated by vehicle weight. The ability to estimate the drag of individual vehicle configurations would provide an analytical basis for improving the accuracy of fuel consumption and exhaust emission testing, and for normalizing Federal Test Procedure test results with respect to drag variations in a given vehicle weight category.

Analytical procedures and supportive test data for the estimation of road vehicle aerodynamic drag are limited. Two procedures[2,3] have been developed based on the "drag rating" method. A drag rating is determined from the qualitative geometric characteristics of the vehicle configuration. The drag rating is then interpreted as a drag coefficient through a correlation curve. Both procedures indicate correlation curves which are linear with the drag rating. These two procedures appear to be limited to the conventional passenger vehicle configuration. Furthermore, since they are based on the interpretation of qualitative characteristics, they lead to inconsistent estimates even when restricted to the passenger class of road vehicles. Therefore, a drag estimating procedure based on quantitative geometric characteristics and applicable to the range of generic body shapes common to the freeways was deemed to be desirable.

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*Superscripts in the text refer to references listed after Section 4.

This investigation was undertaken to develop a simple, relatively accurate procedure for estimating the aerodynamic drag coefficient of road vehicles from easily quantifiable vehicle shape parameters. The method developed 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 preliminary formulation of this method based on the available test data is presented in the main report. Appendix A describes a study of methods for determining vehicle frontal areas from photographs. Also presented, in Appendices B and C, respectively, are bibliographies on the aerodynamic drag of road vehicles and on wind tunnel and full-scale road vehicle aerodynamic testing techniques.

SECTION 2

DRAG PREDICTION METHOD

2.1 APPROACH

The aerodynamic drag force of a body in motion with respect to the surrounding air is given by

$$F_D = \frac{1}{2} \rho u^2 A_{Ref} C_D \qquad (1)$$

where

F_D = force, N (lb)
ρ = mass density of air, kg/m^3 (slugs/ft^3)
u = freestream (or vehicle) velocity, m/sec (ft/sec)
A_{Ref} = reference area, m^2 (ft^2)
C_D = drag coefficient

A knowledge of C_D allows calculation of the vehicle aerodynamic drag over all operating conditions.

Highly accurate and easily applied procedures have been developed by the aircraft industry for estimating the drag of streamlined bodies. Since road vehicle bodies typically are bluff and rather complex, considerable aerodynamic knowledge and experience is required for satisfactory estimation of their drag. Therefore, in the present study, a simplification as in the manner of the drag rating method was sought. The basic approach chosen was that of the "drag build-up" technique wherein the total drag coefficient $C_{D_{TOT}}$ is considered equal to the sum of the contributions of the various components of the vehicle

$$C_{D_{TOT}} = \sum_{i=1}^{n} C_{D_i} \qquad (2)$$

where C_{D_i} is the contribution of the ith component including flow interference effects. Each of the contributions is based on the quantitative geometric measurements of the component and is restricted to the case of zero sideslip (no crosswind) since neither sufficient time nor test data were available in the present effort for the inclusion of crosswind effects. Both full-scale and wind tunnel model data were used to establish the constants which define the contributions of each component. It is noted that these data are limited since much of the relevant work in this area is conducted by the automotive industry and by the Motor Industry Research Association (MIRA) of England and is treated by them as proprietary. As a result, these data were unavailable for incorporation in the present study. Therefore, the quantitative information provided herein must be viewed as preliminary and in need of the further substantiation which would be provided by the acquisition of a broader data base.

2.2 DRAG BUILD-UP

The present formulation breaks the drag of a road vehicle into 11 discrete contributions. The reference area A_R, which is used to normalize all 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, appears in the estimates. The relevant vehicle dimensions and areas are illustrated in Figure 2-1. The details of the drag build-up are as follows.

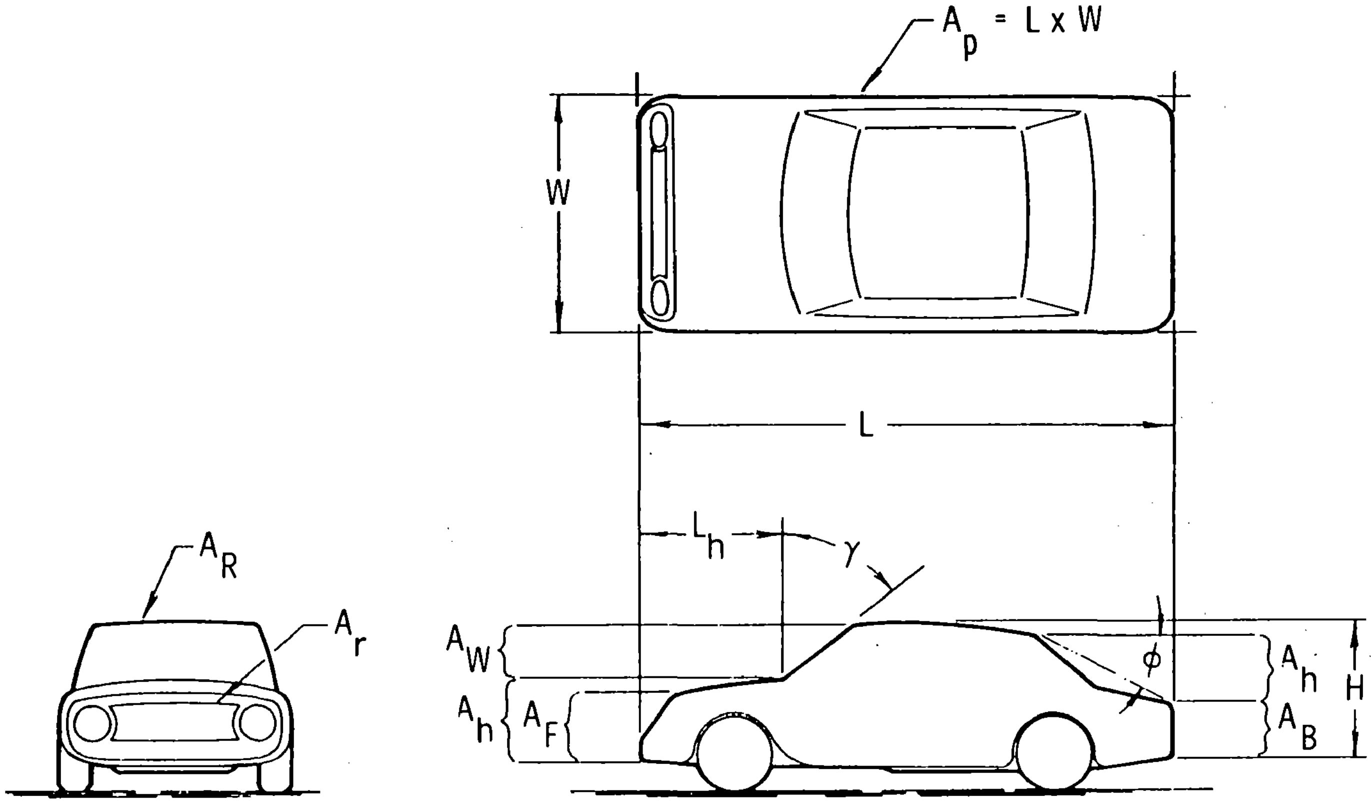

Figure 2-1. Vehicle Dimensions

Front End Drag Coefficient, C_{D_1}—

$$C_{D_1} = 0.707 \left(\frac{A_F}{A_R}\right) \left\{ 1.0 - 2.79 \left(\frac{R}{E}\right)_u + 0.82 \left(\frac{R}{E}\right)_l - 5.21 \left(\frac{R}{E}\right)_v \right.$$

$$\left. - 29.5 \left(\frac{R}{E}\right)_u \left(\frac{R}{E}\right)_l \left[1.0 - 2.25 \left(\frac{R}{E}\right)_v \right] \right\} \qquad (3)$$

where

A_F = front end projected area, m^2 (ft^2)
R = edge radius, m (ft)
E = running 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}-

$$C_{D_2} = 0.707 \left(\frac{A_W}{A_R}\right) \left[1.0 - 2.79 \left(\frac{R}{E}\right)_{u'} \cos\beta - 5.21 \left(\frac{R}{E}\right)_{v'} \right] \cos^2\gamma \qquad (4)$$

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 β 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}-

$$C_{D_3} = 0.707 \left(\frac{A_h - A_F}{L_h}\right)^2 \Big/ A_R \tag{5}$$

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}-

$$C_{D_4} = \begin{cases} -0.19 \left(\frac{R_v}{W}\right)\left(\frac{E_b}{H}\right) & \text{for } \left(\frac{R_v}{W}\right) \le 0.105 \\ -0.02 \left(\frac{E_b}{H}\right) & \text{for } \left(\frac{R_v}{W}\right) > 0.105 \end{cases} \tag{6}$$

where

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

W = vehicle width, m (ft)

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

H = vehicle height, m (ft)

Base Region Drag Coefficient, C_{D_5}-

$$C_{D_5} = 0.15\left[\left(\frac{A_B}{A_R}\right) + \left(\frac{C_{D_H}}{C_{D_B}}\right)\left(\frac{A_H}{A_R}\right)\right] \tag{7}$$

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°) 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 3-2 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}.

$$C_{D_6} = 0.025\,(0.5 - x/L)\left(\frac{A_p}{A_R}\right) \quad \text{for } 0 \le x/L \le 0.5 \qquad (8)$$
$$= 0 \quad \text{for } x/L > 0.5$$

where

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

L = vehicle length, m (ft)

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

Wheel and Wheel Well Drag Coefficient, C_{D_7}

$$C_{D_7} = 0.14 \qquad (9)$$

Rear Wheel Well Fairing Drag Coefficient, C_{D_8}

$$C_{D_8} = -0.01 \qquad (10)$$

Protuberance Drag Coefficient, C_{D_9} —

$$C_{D_9} = \frac{1.1}{A_R} \sum A_{p_j} \tag{11}$$

where

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

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

$$C_{D_{10}} = 0.4 \frac{A_M}{A_R} \tag{12}$$

where

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

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

$$C_{D_{11}} = 1.8 \left(\frac{A_r}{A_R}\right) \left(\frac{u_r}{u}\right) \left[1.0 - 0.75 \left(\frac{u_r}{u}\right)\right] \tag{13}$$

where

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

u_r = exit velocity of cooling air from radiator

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

and

$k = 1.146 \, (m/sec)^{-2}$ [or $0.299 \, (mph)^{-2}$]

SECTION 3

DISCUSSION

The coefficients C_{D_1} through C_{D_4} comprise the bulk of the forebody profile drag. The present method of estimating these quantities is based primarily on the experimental results of Barth,[4] Carr,[5] and Saltzman[6] for rectangular configurations. An examination of these data reveals a dramatic effect due to rounding the edges on the forward face of the models. Figure 3-1 shows these data plotted as a function of edge radius R normalized by the vehicle width W. The data are insufficient to precisely establish the variation of drag with R/W or to determine all of the significant geometric parameters of influence. In the interest of simplicity two straight lines (shown dashed in Figure 3-1) are used to represent the variation. It is assumed that the shape of the variation is the same for any single edge or combination of edges being rounded on a forward facing surface until further data become available.

The effect of rounding the rear edges is considerably smaller than that of rounding the forward edges. Saltzman's full-scale data with an R/W of 0.2 indicate that rounding all of the rear edges results in a drag coefficient decrease of 0.02. This decrease is taken to be that due to rounding the rear vertical edges only, since Carr's results for the effect of rounding the various rear edges did not definitely establish the contribution of the rear lateral edges. Further work is necessary to more accurately determine the drag increments due to rounding the rear edges.

Table 3-1 presents the drag coefficients obtained by Carr[5] in a study of the effects of rounding various front edges. It is noted that the squared front lower lateral edge with all other edges rounded results in a higher drag coefficient than for all edges rounded. However, Carr also presents data for a simple automobile-like configuration which show the opposite effect. The latter trend would be more consistent with the concept that small front spoilers also tend to reduce drag as indicated by Hucho.[8] The bracketed

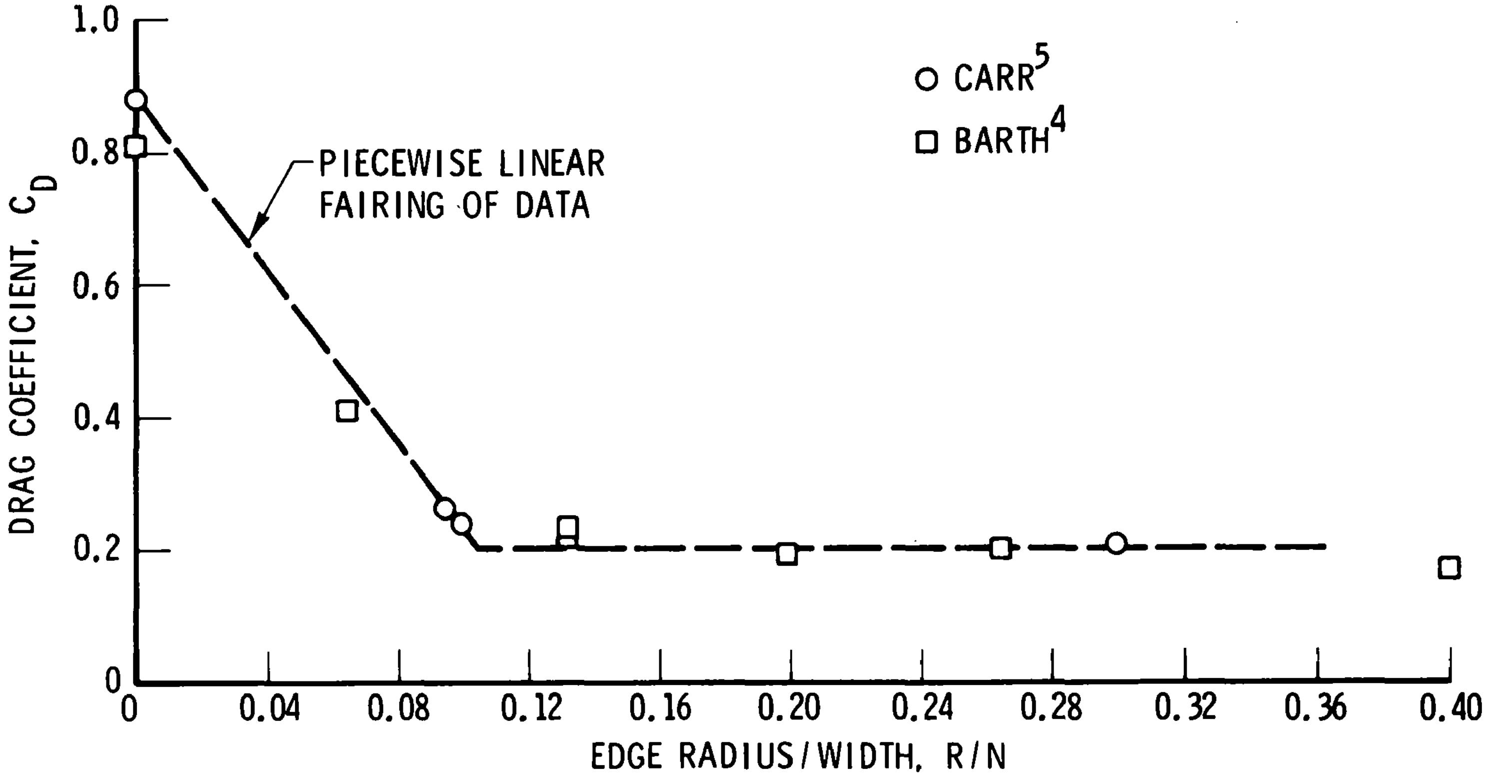

Figure 3-1. Effect of Edge Radius on Drag Coefficient of Rectangular Configurations

Table 3-1. Effect of Rounded Edges

Front			Rear Vertical	Drag Coefficient[a]
Lower	Upper	Vertical		
				0.875
			X	0.857
X		X	X	0.531
X	X		X	0.482
		X	X	0.47
X	X	X		0.29
	X	X	X	0.263
X	X	X	X	0.208
X	X	X	X	[0.27][b]

Width: Height: Length = 1:1:2.5
R/W = 0.3
[a]Carr[5]
[b]Rear lateral edges squared with all other edges rounded.

value 0.27 in Table 3-1, as measured by Carr for the squared rear upper lateral edge with all other edges rounded, is assumed to apply for all edges.

Table 3-2 shows a comparison of the front end drag coefficient C_{D_1} computed using Eq. (3) with that obtained from the full-scale data of Saltzman. In reducing the Saltzman data, the contributions of the wheels and wheel fairings, underbody details, and the base were taken to be 0.14, 0.08, and 0.14, respectively.

The windshield contribution C_{D_2} is assumed to be similar in form to that of the front end with certain modifications. A $\cos^2 \gamma$ factor is applied where γ is the inclination angle of the windshield. This factor, which accounts for the extent of secondary separation at the foot of the windshield, is based on the data of Scibor-Rylski.[9] Also, Carr's data indicate that rounding the

Table 3-2. Comparison of Estimates with Full-Scale Data

Rounded Edges			Drag Coefficients		
Front Lateral	Front Vertical	Rear Vertical	Underbody C_{D_6}	Estimated C_{D_1}	Measured[a] C_{D_1}
			0.08	1.097	1.13
	X	X	0.08	0.69	0.68
X	X	X	0.08	0.49	0.52
X	X	X	0	0.41	0.44
X	X		0	0.43	0.46

Width: Height: Length = 1:0.793:2.5
R/W = 0.2
[a]Saltzman, et al.[6]

roof for windshield inclination angles greater than 45° has no effect on the drag. The term for the radius at the roof-windshield intersection is multiplied by cos β to reflect this behavior. For β greater than 90°, the cos β term is taken to be zero. A comparison of measured and estimated windshield drag values using Carr's data for the 45° windshield results is presented in Table 3-3. Although inaccuracies exist, further refinement would detract from the simplicity of the estimating procedure.

Since the engine hood contribution C_{D_3} appears to be relatively small, the same approach as for the windshield is used. The radius terms are omitted since Carr's data did not show a significant effect due to rounding the corners. A squared cosine factor appears in the windshield contribution to account for the windshield slope effect. Since a single geometric slope for the hood is not available, an "equivalent squared cosine" factor is employed. This factor is $(A_h - A_F)/L_h^2$, the difference between the cross-sectional area at the hood-windshield intersection and the projected front end area divided by the square of the distance between those two areas. This

Table 3-3. Effect of Windshield Angle

Windshield Angle (degrees)	Estimated C_D	Measured C_D [a]
35	0.478	0.468
45	0.460	0.460
55	0.439	0.451
65	0.421	0.434
[a]Carr[5]		

results in an averaged, or effective, squared cosine term. For $(A_h - A_F)$ negative, this term is taken to be zero.

The formulation of C_{D_5}, the drag coefficient contribution of the rear portion, is based on the model test results of Hucho, et al.[7,8] The rear configuration is assumed to be either a hatchback or a notchback. Those configurations with smoothly curved rooflines are treated as hatchbacks with the roof break assumed to start at that point where the roofline slope is 15°. The drag coefficient of the flat base C_{D_B} is taken to be 0.15 while the ratio of hatchback to flat base drag coefficient (C_{D_H}/C_{D_B}) is assumed to be a function of ϕ, the angle from the upper rear roof break to the top of the base area. The variation of (C_{D_H}/C_{D_B}) with ϕ as obtained from the data of Hucho is shown in Figure 3-2.

Saltzman, et al.,[6] present the drag coefficient difference between a smooth underbody and a detailed underbody of a vehicle as 0.08. Taking the plan view area A_p as being the significant area results in the contribution of the detailed underbody above that of the smooth underbody as

$$C_{D_{underbody}} = 0.025\ (A_p/A_R)$$

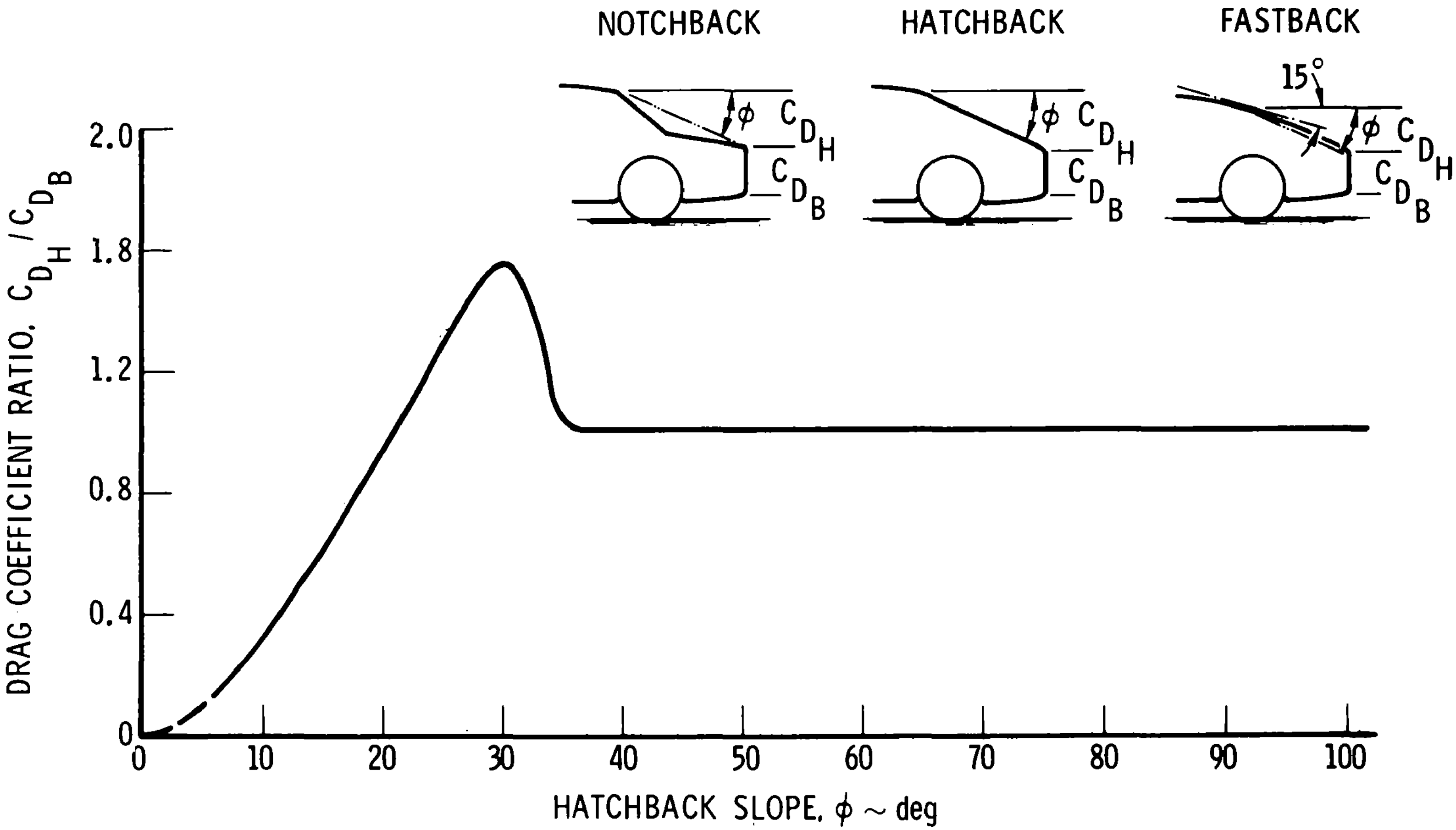

Figure 3-2. Hatchback-Notchback Drag Coefficient Ratio

Beauvais, et. al.,[10] investigated the effect of smoothing the forward fraction x/L of the total length L of the underbody. Linearizing the results for simplicity modifies the above expression to yield the form for C_{D_6} given by Eq. (8).

Test data on the drag of wheels and wheel wells are sparse. Carr's[5] model investigation indicates a value of 0.14. Kyropoulos, et al.,[11] indicate that the removal of wheels from a quarter-scale passenger automobile model results in a decrease of 0.076. If 0.14 is chosen for the wheels and wheel wells, 0.064 would be attributed to the wheel wells. Until further data become available so that relative size effects can be included, C_{D_7}, the contribution due to wheels and wheel wells, will be taken as 0.14. Carr's[12] data for the rear wheel well being covered indicate that this contribution, C_{D_8}, is -0.01.

The contributions of protuberances to vehicle drag, C_{D_9} and $C_{D_{10}}$, are based on the data of Hoerner.[13] The diameters of cylindrical protuberances such as antenna and luggage carrier rails are sufficiently small to ensure subcritical Reynolds number flow even at high vehicle speeds. The drag coefficient for this condition is about 1.1, the same as that for disk-like mirrors and hood ornaments. The drag coefficient for cup-like shapes convex windward is 0.4, the value applied to external mirrors with bullet fairings. In general, the smaller protuberances, mirrors, and hood ornaments will be mounted in regions of accelerated or locally separated flow which will modify the magnitude of their drag contributions. However, such refinements at present are unwarranted.

The cooling drag contribution $C_{D_{11}}$ is based on Olson's[14] air flow measurements through conventional front radiator configurations. Cooling drag is taken to be the change in momentum rate of the flow through the radiator. The mass flow rate $\dot{m}$ through a radiator whose area is A_r is

$$\dot{m} = \rho_r u_r A_r$$

where ρ_r = air density behind radiator, and u_r = average air flow velocity behind the radiator. Freestream values are denoted without subscript. The change in momentum rate is the product of the mass flow rate and the difference between the freestream velocity and the exit velocity. The air from behind the radiator passes over the engine with variations in the horizontal velocity occurring due to flow cross-section area, heat exchange with the engine, viscous effects, and mixing with secondary air flow. In order to simplify the problem, the exit velocity is assumed to be 0.75 u_r. Thus, the cooling drag coefficient becomes

$$C_{D_{cooling}} = \dot{m} \frac{(u - 3/4\ u_r)}{(1/2\ \rho u^2\ A_r)}$$

With the added assumption that the radiator-to-freestream density ratio is 0.9 due to heat transfer from the radiator, Eq. (13) is obtained for $C_{D_{11}}$ as a function of the velocity ratio (u_r/u). If simplicity is of no concern, the energy exchange and the losses through the radiator can be included in the estimate. Olsen's data in modified form are presented in Table 3-4. It is assumed that the incremental air flows due to configuration changes are independent. Since the magnitudes shown at each velocity are nearly the same, they were averaged for the two test vehicles and assumed linear with respect to velocity to result in the variation of (u_r/u) given by Eq. (14).

In the present formulation, the skin friction contribution is considered to be included in the profile drag coefficients, C_{D_1} through C_{D_4}. In general, the magnitude of the skin friction and its variation with Reynolds number or vehicle speed are relatively small so that attempts to isolate these effects are not warranted at this time.

Table 3-4. Radiator Air Flow[a]

Vehicle	Speed (mph)	Flow Rate (cfm)	Fraction Flow Rate After Losses	Fraction Initial Flow Rate Recovered
1974 Pinto $A_r = 2.08\ ft^2$	30	1340	0.373	0.559
	60	3030	0.545	0.258
1974 Mustang $A_r = 2.36\ ft^2$	30	1440	0.347	0.656
	60	3240	0.537	0.275

Losses due to bumper and grill
Recovery due to radiator fan and shroud
[a]Olsen[14]

SECTION 4

CONCLUDING REMARKS

Since the drag contributions of the various vehicle components are not independent, formulations of aerodynamic force estimations are generally limited to similar configurations where interference effects between components are also similar. Nevertheless, it is believed that the present expressions are applicable to conventional passenger vehicles, station wagons, and vans. Only a few simple checks have been made since accurate configuration data were not on hand for reliable comparison. Thus, the task remains for the present drag estimation procedure to be tested for validity.

Several assumptions were incorporated in the present formulation of a drag estimation procedure to retain the primary objective of simplicity of application. Also, the limited test data available and the level of effort allotted imposed restrictions on the scope and depth of the analysis. For example, the drag reduction due to rounded edges is of concern because of the large effect demonstrated by the experimental information. The assumed variation should be redefined if necessary. Further effort is warranted to determine the effective radius for edges of noncircular shape. Other shaped corners, for example elliptical, should be compared with the circular to determine the relative sizes for similar overall effect on the leading edge suction and influence on flow away from the corners.

The drag coefficient for a flat base has been taken as constant in the present formulation without regard to changes to the configuration. The experimental base pressure coefficient measurements presented by Saltzman demonstrate that variations occur due to rounding the rear edges. Hoerner[13] presents a base drag coefficient variation as a function of forebody drag, but it is applicable only to the condition of well-behaved, nonseparated flow ahead of the base of bodies of revolution. Since motor vehicles operate with a variation of flow conditions around the periphery of the base, a study of the effect on the average base pressure would be desirable.

Several factors which influence vehicle drag have been, by necessity, omitted from the present analysis. Among the more important are drag due to lift, crosswind effects, vehicle ground clearance, and certain detail features of the geometry. Examples of the latter are front end treatment where deep set headlights can produce two to three times the drag of flush-mounted lights, strakes or side fences which fair the line between the rear window and rear hood on notchbacks and which by their fencing action increase the base drag, and chin spoilers and rear deck dams or upturns which, when properly designed, have been shown to reduce vehicle drag. These factors deserve detailed consideration and where found warranted should be incorporated in the present method to improve its accuracy and scope of application.

Finally, it is considered necessary to apply the present method of drag estimation to the available EPA roll-down data on current models. These data are uncontaminated by wind tunnel interference effects and should be of high quality. Such a comparison will provide the best opportunity for refining and, where necessary, revising the details of the present method.

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APPENDIX A

ROAD VEHICLE FRONTAL AREA AS DETERMINED FROM PHOTOGRAPHS

A.1 INTRODUCTION AND BACKGROUND

In EPA certification testing of light-duty vehicles,[1] the component of the dynamometer power absorption unit setting which represents aerodynamic drag is determined from a table of road-load power settings defined for a discrete set of vehicle weights. However, aerodynamic drag is more accurately represented as a function of vehicle size and geometry. Various drag estimation methods which reflect these two factors are being investigated by EPA for comparison with current procedures.

In the prediction of aerodynamic drag, the size factor is represented by a reference area A_{Ref}, typically the vehicle projected frontal area, while the effect of geometry is accounted for by the drag coefficient C_D. Methods for predicting C_D were developed and are reported in the body of this report while the results of a study of methods for determining A_{Ref} from 35 mm negatives are presented herein.

In general, the contours of road vehicles are too complex to permit direct measurement of A_{Ref} and no detailed drawings or loft lines are provided by the manufacturer from which this quantity may be obtained. In the field, measurements of A_{Ref} are most readily obtained from front view photographs of the vehicle. In the present study, available methods were investigated by which the projected frontal area of road vehicles can be determined from 35 mm photographic negatives and the preferred method was selected and applied to a set of negatives provided by EPA. The results of this effort as well as an assessment of the accuracy of the selected method are discussed in the following sections.

[1] Federal Register, 40 (126), Part III, "Environmental Protection Agency — Control of Air Pollution from New Motor Vehicles and Engines" (30 June 1975).

A.2 FRONTAL AREA DETERMINATION PROCEDURE

The 35 mm negatives provided by EPA consisted of front, side, and rear views as well as three-quarter front and rear views of 77 road vehicles. Included in this set were 56 passenger sedans, five station wagons, five vans, eight pick-up trucks, and three sports cars. A 0.2 m x 0.2 m (0.656 ft x 0.656 ft) square was attached to the front of each vehicle to provide a dimensional reference. Glossy 8 in. x 10 in. enlargements were made from the 35 mm negatives and were used for all subsequent analyses. A typical front view is shown in Figure A-1. Apparent in this photo are the strong effects of perspective which result from the proximity of the camera to the vehicle and which cause a distortion of the projected area for all surfaces aft of the plane containing the reference square. This effect, shown schematically in Figure A-2, not only contracts dimensions in receding planes but also causes a distortion of the front hood and roof projected area due to differences in elevation between the camera and these surfaces. Also of note in Figure A-1 is the poor definition of the underbody contour which is almost totally lost in shadow.

Measurement of the projected frontal area from the 8 x 10 prints must be preceded by a definition of the underbody contour and a correction of the windshield-roof contour for the effects of perspective. Once this has been done, the physical measurements of the corrected vehicle contour and reference square can be made by some appropriately chosen technique and these areas used in a straightforward fashion to compute A_{Ref}. In the present study, the definition of the underbody contour was greatly facilitated by viewing the prints on a light table. The correction of the windshield-roof contour and front hood and roof areas for the effects of perspective was accomplished by utilization of all views of the road vehicle to pick up visual keys such as the slope of the front hood and the ratios of windshield-hood intersection width and rear window width to vehicle maximum width. These clues were then used to construct on an overlay a best estimate of the true projected contour of the windshield-roof line.

Figure A-1. Passenger Sedan, Front View

Figure A-1. Passenger Sedan, Front View

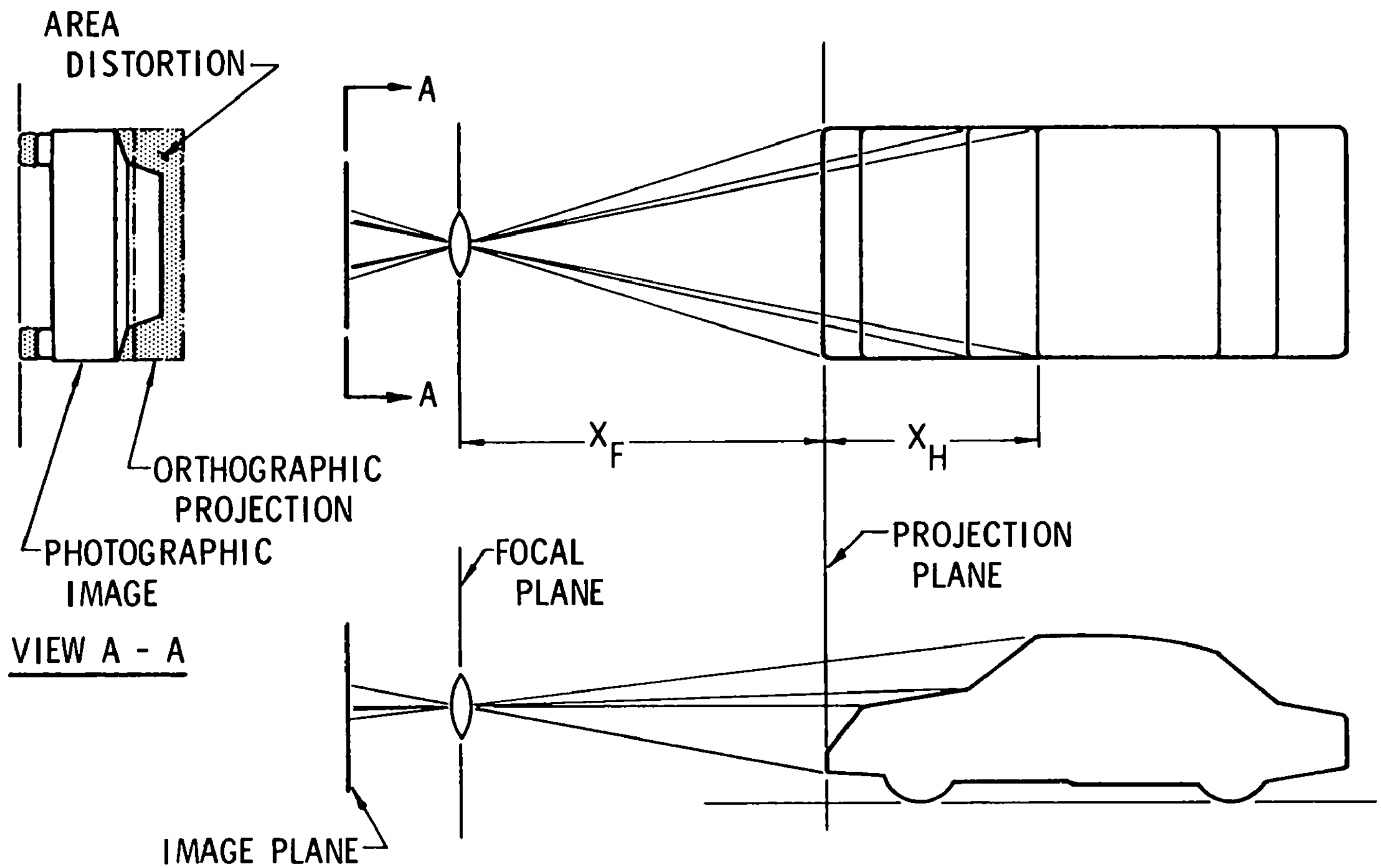

Figure A-2. Schematic of Front View Photographic Projection

Two techniques were considered for the measurement of the corrected projected frontal area: direct measurement by planimetry, and use of a laboratory grade balance to determine the ratio of the projected frontal area cut from the photograph to the area of the reference square. Both techniques require the use of precision equipment, a planimeter or a laboratory scale, so that no advantage is apparent here. Also, the accuracy of the two procedures is considered to be equivalent. This point is discussed further in Section A-4. The essential difference between these two methods is that planimetry is nondestructive and allows preservation of the basic data and repeatability checks of the perspective corrections and area measurements. It is on this basis that planimetry was selected as the preferred method of area measurement.

A.3 AREA MEASUREMENT RESULTS

The procedure described above for the measurement of A_{Ref} from 35 mm negatives was applied to the set of 77 road vehicles provided by EPA; results are presented in Table A-1. The reference area A_{Ref} is defined as the orthographic projection on a vertical plane of the frontal area of the vehicle including tires and underbody details but excluding protuberances such as mirrors, antenna, and luggage carriers. The projected frontal area excluding the exposed tires is also presented and is denoted A'_{Ref}. The A'_{Ref} is included as it may be found to be a useful parameter in future correlations of predicted and measured aerodynamic drag.

The vehicles are grouped according to type and it is of interest to note that while the A_{Ref} of the passenger sedans and station wagons varies from about 1.30 m^2 (14 ft^2) to 2.00 m^2 (21 ft^2), the A_{Ref} of the vans is typically about 2.8 m^2 (30 ft^2). The large frontal area of the van in conjunction with its large drag coefficient provides a good indication of the relatively large power requirements of this type of vehicle in highway travel.

A.4 MEASUREMENT ACCURACY

Two sources of error can be identified with the selected procedure for measuring A_{Ref}: those associated with the photographic documentation

Table A-1. Road Vehicle Frontal Area Summary

Type, Make, and Model	License Number or Other Identification	Total Area, A_{Ref} (m²)	Total Area, A_{Ref} (ft²)	Area Sans Tires, A'_{Ref} (m²)	Area Sans Tires, A'_{Ref} (ft²)
PASSENGER SEDAN					
American Motors Gremlin	135 QN (Ohio)	1.386	14.92	1.298	14.08
Pacer	VKW 072 (Michigan)	1.579	16.98	1.495	16.08
Buick Apollo	J7927 (Ohio)	1.705	18.38	1.590	17.14
Century	347 043 (Ohio)	1.847	20.11	1.732	18.87
Le Sabre	J8494 (Ohio)	1.835	19.70	1.751	18.80
Skyhawk	J7977 (Ohio)	1.432	15.42	1.344	14.47
Skylark	J7974 (Ohio)	1.631	17.57	1.513	16.30
Special	J8619 (Ohio)	1.798	19.37	1.674	18.04
Chevrolet Chevelle	6178RU (Ohio)	1.702	18.31	1.577	16.97
Vega	347 012 (Ohio)	1.456	15.69	1.355	14.60
Impala	199 QN (Ohio)	1.876	20.20	1.752	18.87
Monza	347 081 (Ohio)	1.427	15.36	1.334	14.36
Chrysler Newport	11M228 (Michigan)	1.865	20.09	1.794	19.32
New Yorker	PHK134 (Michigan)	1.865	20.09	1.757	18.88
Datsun B210	1350 (Michigan)	1.384	14.91	1.298	13.99
280Z	DTM82 (New Jersey)	1.306	14.06	1.208	13.00
Dodge Dart Sport	10M905 (Michigan)	1.501	16.16	1.402	15.10
Fiat 128	MFR 22AZ (Illinois)	1.461	15.74	1.384	14.91
Ford Capri	EPA358 (U.S. Govt.)	1.291	13.89	1.194	12.85
Capri II GT	21M005 (Michigan)	1.377	14.81	1.300	13.98
Granada	PDF447 (Michigan)	1.661	17.88	1.536	16.53
Granada	Body Marking 844	1.760	18.97	1.640	17.68
Gran Torino	14M495 (Michigan)	1.569	17.95	1.732	16.56
Gran Torino	TFJ540 (Michigan)	1.680	18.05	1.578	16.95
LTD	NJG477 (Michigan)	1.807	19.42	1.697	18.24
LTD	14M494 (Michigan)	1.885	20.27	1.757	18.89

Table A-1. Road Vehicle Frontal Area Summary (cont'd)

Type, Make, and Model	License Number or Other Identification	Total Area, A_{Ref} (m^2)	Total Area, A_{Ref} (ft^2)	Area Sans Tires, A'_{Ref} (m^2)	Area Sans Tires, A'_{Ref} (ft^2)
LTD	14M572 (Michigan)	1.798	19.37	1.676	18.10
Maverick	21M067 (Michigan)	1.620	17.49	1.518	16.39
Mustang II	21M056 (Michigan)	1.565	16.86	1.440	15.52
Mustang II - Mach I	21M057 (Michigan)	1.414	15.23	1.275	13.73
Mustang II - Mach I	21M068 (Michigan)	1.408	15.15	1.297	13.96
Pinto	146QN (Ohio)	1.461	15.72	1.346	14.49
Thunderbird	21M113 (Michigan)	1.747	18.82	1.617	17.42
Torino	17M842 (Michigan)	1.756	18.90	1.636	17.61
Honda CVCC	No. I. D.	1.516	16.31	1.424	15.32
Lincoln Continental	FVL183 (Michigan)	1.981	21.32	1.856	19.98
Mazda	416D61 (Michigan)	1.526	16.41	1.437	15.45
Mercury Marquis	1349 (Michigan)	1.900	20.28	1.766	19.03
Montego	Body Marking 733	1.841	19.82	1.735	18.68
Oldsmobile Cutlass Supreme	198QN (Ohio)	1.841	19.81	1.720	18.51
Cutlass Supreme	7937RU (Ohio)	1.757	18.90	1.640	17.64
Delta 88	170QN (Ohio)	2.020	21.70	1.900	20.41
Plymouth Gran Fury	11M227 (Michigan)	1.807	19.44	1.668	17.95
Scamp	11M248 (Michigan)	1.719	18.52	1.600	17.24
Valiant Custom	11M232 (Michigan)	1.556	16.76	1.450	15.66
Valiant Custom	G1222746 (U.S. Govt.)	1.624	17.46	1.527	16.43
Pontiac Firebird	506751 (Ohio)	1.492	16.10	1.377	14.86
Le Mans	164QN (Ohio)	1.774	19.10	1.640	17.66
Le Mans	173QN (Ohio)	1.802	19.40	1.669	17.97
Ventura	194QN (Ohio)	1.568	16.84	1.467	15.75
Saab 99 EMS	MFR 25C (Illinois)	1.323	14.25	1.211	13.05

Table A-1. Road Vehicle Frontal Area Summary (cont'd)

Type, Make, and Model	License Number or Other Identification	Total Area, A_{Ref} (m^2)	Total Area, A_{Ref} (ft^2)	Area Sans Tires, A'_{Ref} (m^2)	Area Sans Tires, A'_{Ref} (ft^2)
Toyota Celica	MFR DTM9887(New Jersey)	1.318	14.00	1.219	13.93
Corolla	No I.D.	1.401	15.10	1.311	14.13
Volkswagen Beattle	155QN (Ohio)	1.436	15.46	1.341	14.44
Rabbit	RCM581 (Michigan)	1.460	15.17	1.370	14.20
Volvo 264 DL	HTE061	1.746	19.00	1.652	17.99
STATION WAGON					
Buick Estate Wagon	J7971 (Ohio)	1.842	19.85	1.727	18.61
Chevrolet Impala Wagon	139QN (Ohio)	1.921	20.68	1.790	19.27
Ford Gran Torino Squire	21M114 (Michigan)	1.728	18.60	1.609	17.32
Torino Squire	21M112 (Michigan)	1.758	18.91	1.665	17.91
Plymouth Fury Wagon	10M838 (Michigan)	1.766	19.03	1.650	17.78
VAN					
Chevrolet Beauville					
Sport Van 30	13M942 (Michigan)	3.048	32.82	2.856	30.75
Chevy Van 10	13M818 (Michigan)	3.060	33.00	2.900	31.28
Chevy Van 20	13M823 (Michigan)	2.972	32.00	2.768	29.80
Dodge Tradesman 100 van	19M589 (Michigan)	2.737	29.47	2.658	28.62
Ford Econoline 150 van	7928 HV (Michigan)	2.758	29.69	2.620	28.21
PICK-UP TRUCK					
Chevrolet Cheyenne 10	13M807 (Michigan)	2.440	26.25	2.254	24.25
Cheyenne 20	13M845 (Michigan)	2.470	26.60	2.270	24.45
Scottsdale Van 10	13M805 (Michigan)	2.488	26.80	2.323	25.03
Datsun Pick-up	1343 (Michigan)	1.649	17.74	1.538	16.55
Ford F-100 Pick-up	14M535 (Michigan)	2.431	26.21	2.251	24.27
F-100 Pick-up	21M115 (Michigan)	2.452	26.41	2.319	24.98
F-250 Pick-up	7378HV (Michigan)	2.486	26.80	2.331	25.13

Table A-1. Road Vehicle Frontal Area Summary (cont'd)

Type, Make, and Model	License Number or Other Identification	Total Area, A_{Ref}		Area Sans Tires, A'_{Ref}	
		(m^2)	(ft^2)	(m^2)	(ft^2)
Toyota Pick-up	No. I.D.	1.650	17.79	1.535	16.55
SPORTS CAR					
Chevrolet Corvette Coupe	13M846 (Michigan)	1.332	14.35	1.196	12.89
Triumph TR-6 Top On	No I.D.	1.309	14.09	1.218	13.11
TR-6 Top Off	No I.D.	1.186	12.78	1.094	11.78

and image correction and those associated with the precision of planimetry. The errors associated with planimetry of the corrected vehicle contour were examined by performing a controlled series of planimetry checks on a set of five vehicle contours. At various stages of the study, each of the five contours was planimetered several times by three technicians to establish the consistency with which the operation could be performed. A total spread in A_{Ref} of 1% or less was obtained in all cases.

The major sources of error were found to be photographic distortion of the projected area due to perspective and poorly defined underbody contours. This results because the corrections for perspective and obscured contours are not precise; they require judgment, a good eye, and some artistic skill. An indication of the magnitude of these errors is obtained by comparing the data from Table C-1 for those vehicles with the same body style. There are seven such cases, four consisting of two cars and three consisting of three cars. The comparison is shown in Table A-2, the last column of which lists $\Delta A_{Ref}/\overline{A}_{Ref}$, the ratio of the maximum difference in measured A_{Ref} to the mean A_{Ref} for each case. The mean value of $\Delta A_{Ref}/\overline{A}_{Ref}$ for the seven cases is 0.0483. This quantity is representative of the total error obtained and includes the effects of planimetry as well as perspective. However, these two effects are independent and would be combined statistically by root-sum-squaring. Since the mean total error is larger than the planimetry error by a factor of five, it is clear that the mean $\Delta A_{Ref}/\overline{A}_{Ref}$ is essentially a measure of the error due to perspective.

The errors due to perspective can be reduced by photographing at a greater distance from the vehicle, and by use of reference squares and scales at the vehicle base and at intermediate stations such as the windshield-roof break line as well as at the front. Referring to the schematic of Figure A-2, the deviation of the windshield-roof break line length from the true projected length varies as $(1 + X_H/X_F)^{-1}$, where X_H is the distance of the break line aft of the projection plane, taken here as the vehicle front, and X_F is the distance of the camera ahead of the projection plane. It is desirable to make X_F at least one order (preferably two orders) of magnitude larger than X_H.

Table A-2. A_{Ref} Comparison of Similar Vehicles

Vehicle	A_{Ref} (m^2)	$\bar{A}_{Ref}$ (m^2)	ΔA_{Ref} (m^2)	$\frac{\Delta A_{Ref}}{\bar{A}_{Ref}}$
Ford Granada	1.661 1.760	1.711	0.099	0.0579
Ford Gran Torino	1.669 1.680 1.756	1.702	0.087	0.0511
Ford LTD	1.807 1.885 1.798	1.830	0.087	0.0475
Ford Mustang II	1.565 1.414 1.408	1.462	0.157	0.1074
Plymouth Valiant Custom	1.556 1.624	1.590	0.068	0.0428
Pontiac Le Mans	1.774 1.802	1.788	0.028	0.0157
Ford Gran Torino Squire	1.728 1.758	1.743	0.030	0.0172
Mean Value of $\frac{\Delta A_{Ref}}{\bar{A}_{Ref}} = 0.0483$				

A second benefit of a larger stand-off distance is that the vehicle underside will be more strongly silhouetted and more clearly defined.

An additional point to consider is placement of the reference square. Typically, the vehicle is largest at some station in the midsection and it is the cross-sectional area at this station which must be used as the vehicle reference area A_R. It is imperative that the camera be placed far enough from the vehicle so that A_R is imaged on the film rather than a more forward cross-section of lesser area. If A_R can be imaged on the film and if the reference square is located at A_R, no error is introduced regardless of the vehicle-to-camera distance. The problem is locating the station of maximum cross-section and the possibility that the projected area is greater than any single cross-section. The latter case frequently occurs because of wheel wells flared for tire clearance in the front fenders.

The effect of locating the reference square at an incorrect station is determined as follows. From geometric optics

$$\frac{i}{s'} = \frac{o}{s} \tag{A-1}$$

and from the thin lens formula

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'} \tag{A-2}$$

where

- i = image size
- s' = image distance
- o = object size
- s = object distance
- f = focal length of lens

Combining Eqs. (A-1) and (A-2)

$$i = \frac{of}{(s - f)} \tag{A-3}$$

or, since $s \gg f$

$$i \simeq \frac{of}{s} \tag{A-4}$$

By logarithmic differentiation of Eq. (A-4)

$$\frac{di}{i} = -\frac{ds}{s} \qquad \text{(A-5)}$$

If A_R is to be determined to within ±2%, the linear dimensions must be determined to within ±1%. Accordingly, if the uncertainty in the station for A_R is ±1 m (3.28 ft), then to ensure a 2% error or less in area, Eq. (A-5) states that the camera-vehicle distance must be greater than 100 m (328 ft).

From these considerations, it is seen that the camera-vehicle distance criterion is more appropriately two orders of magnitude greater than either the uncertainty in the Station for A_R or the separation between cross-sections where maxima of local projected regions may occur.

Photographing at large distances will require either a lens of very large focal length, so that a normal size image will be produced on the negative, or extreme enlargement of a negative which is made using a lens of more conventional focal length. Use of a large focal length lens is preferable since sharper prints can be obtained. (The use of a light background such as a portable screen of white paper will also facilitate a sharp definition of the vehicle contour.)

By use of a large camera stand-off distance to minimize perspective and by use of discretely placed reference squares and scales to minimize errors in the correction of that perspective which remains, it is considered possible to reduce these sources of error to the level of the planimetry error.

A-5. SUMMARY AND CONCLUSIONS

Available methods were investigated by which the projected frontal area of road vehicles can be determined from 35 mm photographic negatives. Planimetry of a photographic enlargement, the contours of which have been corrected for the effects of perspective, is considered the most desirable procedure. Application of this procedure to a set of 35 mm negatives indicates the total error to be about 5% and to be due primarily to the effects of perspective and to the poor definition of the underbody contour.

It is concluded that, for consistent results, the front view photographs must be taken at distances at least one order of magnitude greater than the vehicle length and that a light uniform background should be used to sharpen the vehicle contour. By use of these procedures, it is considered that the total error in vehicle measured projected frontal area can be reduced to less than 2%.

APPENDIX B

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16. ABSTRACT

A simple procedure was developed for the estimation of road vehicle aerodynamic drag based on easily quantifiable vehicle shape parameters. The procedure is applicable to passenger vehicles, station wagons, and vans and is based on a "drag build-up" method which includes the effects of the basic body shape, underpanning, and cooling drag. Not included are effects of lift, sidewind, ground clearance, and certain shape details. The limitations of the procedure are discussed and improvements and areas requiring further study are identified. In a related activity, a brief investigation was made of possible techniques for determining vehicle frontal area from photographs of cars. Planimeter measurements of frontal area were made from photographic enlargements of approximately 80 cars. The results of this effort are included as an appendix. Bibliographies on road vehicle aerodynamic drag and on wind tunnel and full-scale road testing techniques are also appended.

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