

Aerodynamic Drag of Passenger Cars at Yaw

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ABSTRACT

The aerodynamic drag characteristics of a passenger car are typically defined by a single parameter, the drag coefficient at zero yaw angle. While this has been acceptable in the past, it may not allow a true comparison between vehicles with regard to the impact of drag on performance, especially fuel economy. An alternative measure of aerodynamic drag should take into account the effect of non-zero yaw angles and some proposals have been made in the past, including variations of wind-averaged drag coefficient. For almost all cars the drag increases with yaw, but the increase can vary significantly between vehicles. In this paper the effect of various parameters on the drag rise with yaw are considered for a range of different vehicle types. The increase of drag with yaw is shown to be an essentially induced drag, which is strongly dependent on both side force and lift. Shape factors which influence the sensitivity of drag with yaw are discussed.

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INTRODUCTION

Aerodynamic drag of passenger cars is once again the focus of much activity by all manufacturers. This is primarily driven by environmental concerns, mainly relating to increasing CO₂ levels in the atmosphere. This has led to renewed interest in improving vehicle efficiency by reducing the overall resistance to motion. Aerodynamic drag is a significant contributor to that resistance, especially at higher vehicle speeds.

Considerable reductions in car aerodynamic drag have been made over time, as development techniques have been refined and test procedures improved to represent the car on the road. The car drag is characterized by the drag coefficient measured at zero yaw and this is the primary aerodynamic target for all OEMs. It is, however, determined in a low turbulence environment and this value is not necessarily representative of the aerodynamic resistance experienced in the real world. A natural wind of some magnitude is almost always present and vehicles rarely operate in complete isolation. The car will usually experience an onset flow which is both turbulent and yawed.

In an attempt to quantify the effect of this yawed flow on the performance of a car various proposals have been made. The simplest measure is to determine the drag coefficient at a representative average yaw angle. Many OEMs have a secondary drag target; the drag coefficient at 5° or 10° yaw angle. For a more complex approach different forms of a wind averaged drag coefficient have been advocated. There are objections to each method and no agreement on a common approach. In part this results from the very large range of possible wind speed and direction experienced on the road and the wide variation in local roadside environments.

It is not the intention in this paper to assess the different methods but to explore the drag characteristics of a car at yaw. The drag of a highly streamlined vehicle may reduce with yaw but for passenger cars the drag will almost always initially increase with yaw. For yaw angles up to approximately 15° the drag coefficient increases substantially for all cars, but then levels off before reducing at higher yaw angles. In some cases at very small yaw angles drag may decrease, but at yaw angles above approximately 5°, the drag coefficient exceeds that obtained at zero yaw. The drag rise with yaw varies for different types of vehicle, but can also vary substantially for vehicles of similar shape and size.

While there is considerable variation in the drag increase with yaw, it is not related to the drag at zero yaw. As shown by Windsor, [1], some cars with a low zero yaw drag coefficient can have a very high increase in drag at yaw. There is, consequently a reduced impact on vehicle performance in the real world because the benefit of the nominally low drag coefficient is offset by the increased drag at non-zero yaw angles.

In this paper the drag increase at yaw is shown to be dependent on both side force and lift. As the side force variation with yaw for given vehicle types is small, lift is seen to be an influential parameter.

DRAG AT YAW

The increase in drag coefficient with yaw can vary considerably for cars of similar shape as well as for cars of different types. Figure 1(a), (b), (c), (d) demonstrates this for a range of cars in the MPV, small hatchback, SUV and saloon car categories respectively, which represent 1-box, 2-box and 3-box shapes. The data has been obtained for cars which have been on sale in the recent past. All the cars were

tested in the MIRA full scale wind tunnel. This wind tunnel has a closed working section, 7m wide and 5m high, (35m² cross section) and 15m long, with an open return. The wind tunnel has a fixed ground plane. The standard MIRA corrections for blockage and pressure gradient have been applied. The cars were set up in the wind tunnel according to the EADE (European Aerodynamic Data Exchange) standard, with the exception that the nominal airspeed for all testing was 27m/s.

The principal dimensions; length, width, height and frontal area, of the cars for which aerodynamic data has been presented are given in Tables 1(a), (b), (c), (d), which accompany each graph.

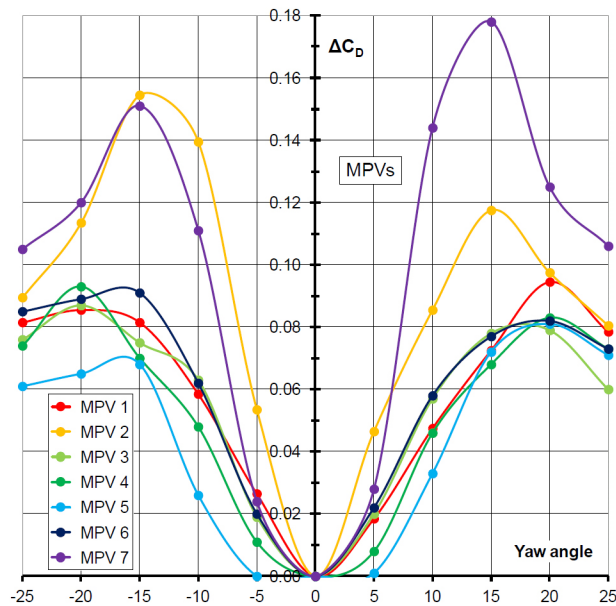


Figure 1(a). Drag increase with yaw angle for a range of MPVs.

Table 1(a). Principal dimensions for the MPVs.

Vehicle	L (m)	W (m)	H (m)	A (m ²)
MPV 1	4.64	1.84	1.63	2.62
MPV 2	4.28	1.75	1.63	2.41
MPV 3	4.14	1.72	1.60	2.40
MPV 4	4.62	1.81	1.73	2.73
MPV 5	4.76	1.79	1.64	2.53
MPV 6	4.32	1.71	1.86	2.70
MPV 7	4.75	1.80	1.78	2.81

The data presented in this paper is for yaw angles in the range -25° to $+25^\circ$, although the data was obtained for yaw angles up to 30° or 35° to make the trends through the 25° yaw angle accessible.

Figure 1 shows that in all categories of cars the variation in the drag increase with yaw is considerable. For the 1-box and 2-box shapes the drag coefficient increase at 10° yaw is typically in the range 0.03 to 0.06, but examples are shown where the drag coefficient increase exceeds 0.10. For the saloon car shapes the drag rise tends to be lower. In all categories it can be noted that some cars demonstrate a considerable asymmetry in the drag-yaw curves.

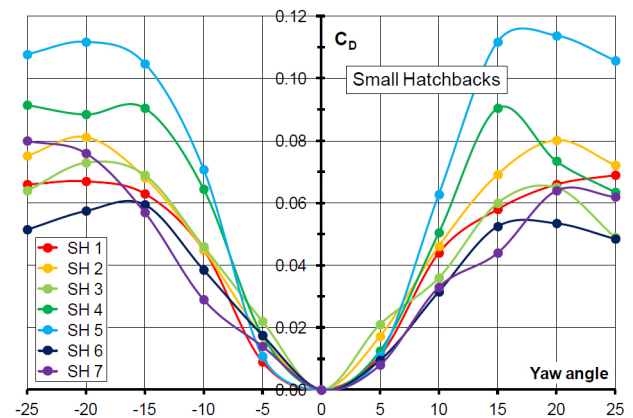


Figure 1(b). Drag increase with yaw angle for a range of small hatchback cars.

Table 1(b). Principal dimensions for the small hatchback cars.

Vehicle	L (m)	W (m)	H (m)	A (m ²)
SH 1	3.97	1.72	1.50	2.18
SH 2	3.94	1.71	1.49	2.21
SH 3	4.03	1.69	1.49	2.20
SH 4	4.05	1.72	1.46	2.16
SH 5	3.96	1.74	1.46	2.14
SH 6	3.85	1.70	1.51	2.20
SH 7	3.97	1.68	1.46	2.09

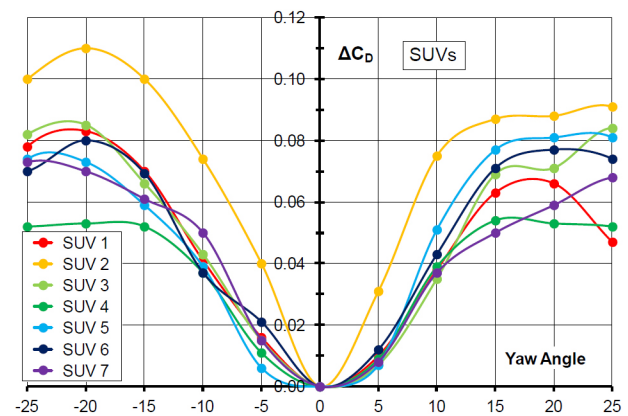


Figure 1(c). Drag increase with yaw angle for a range of compact SUVs.

Table 1(c). Principal dimensions for the compact SUVs.

Vehicle	L (m)	W (m)	H (m)	A (m ²)
SUV 1	4.39	1.80	1.76	2.63
SUV 2	4.50	1.82	1.73	2.63
SUV 3	4.51	1.76	1.68	2.52
SUV 4	4.61	1.82	1.86	2.80
SUV 5	4.58	1.78	1.71	2.55
SUV 6	4.74	1.88	1.66	2.65
SUV 7	4.57	1.85	1.67	2.60

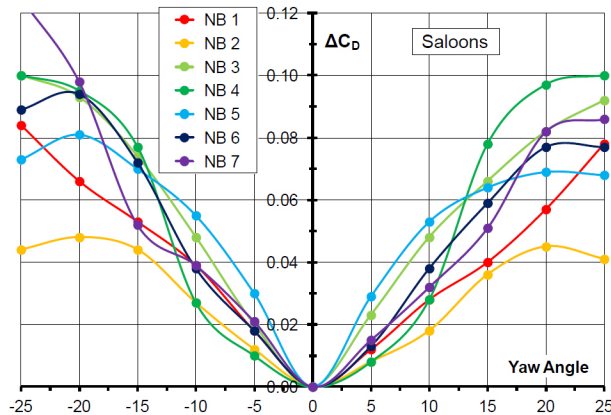


Figure 1(d). Drag increase with yaw angle for a range of saloon cars.

Table 1(d). Principal dimensions for the saloon cars.

Vehicle	L (m)	W (m)	H (m)	A (m ²)
NB 1	4.92	1.87	1.46	2.30
NB 2	4.71	1.85	1.39	2.23
NB 3	5.07	1.90	1.48	2.48
NB 4	4.58	1.77	1.45	2.20
NB 5	4.83	1.86	1.50	2.37
NB 6	4.47	1.74	1.42	2.06
NB 7	4.73	1.81	1.43	2.17

For the 1-box category; MPVs, the vehicles are comparable in shape, but the slope of the front end can vary. The variation in length, width and height is considerable, and the frontal area ranges from 2.4 to 2.8m². In the case of the small hatchbacks, representing 2-box shapes, the cars are all of similar shape and size. The shapes of some cars in this category approach the 1-box type as the bonnet and windscreen angles are similar. The frontal areas are in a narrow range from 2.1 to 2.2m², but it can be seen in Figure 1(b) that there is still a substantial variation in the drag rise at yaw. In the other, larger, 2-box category, represented here by a range of compact SUVs, the shapes can vary significantly as can the width and height dimensions. All have a significantly notched front end and the frontal areas range from 2.5 to 2.8m². The 3-box saloon cars are of very different lengths and widths. The shapes range from a classic notchback to a near fastback configuration and the frontal areas vary substantially from 2.1m² to 2.5m².

INDUCED DRAG

Mercker, [2], has shown that the increase in drag at yaw is essentially an induced drag, based on the combination of lift and side force. The increase in drag for a significant range of yaw angles can be expressed as:

$$C_{Di} = K(C_L^2 + C_Y^2) \quad (1)$$

Where C_L is the lift coefficient, C_Y is the side force coefficient and C_{Di} is the wind axis drag coefficient and is given by:

$$C_{Di} = C_{D0}\cos\psi + C_Y\sin\psi \quad (2)$$

In general terms this wind axis drag component is identified here as CDR to avoid any uncertainty regarding the use of the induced drag term. It has been derived for the same range of cars in the different vehicle categories as presented in Figure 1 and the results are shown in Figures 2(a), (b), (c), (d).

Both axes represent the increase from the zero yaw condition, such that:

$$\begin{aligned} \Delta C_{DR} &= C_{DR\psi} - C_{DR0} \quad \text{and} \\ \Delta(C_L^2 + C_Y^2) &= (C_L^2 + C_Y^2)\psi - (C_L^2 + C_Y^2)_0 \end{aligned}$$

where the suffices ψ and 0 denote yaw angles.

In the case of the ΔC_{DR} term;

$C_{DR0} = C_{D0}$, the drag coefficient at 0° yaw,

while for the function $\Delta(C_L^2 + C_Y^2)$;

$(C_L^2 + C_Y^2)_0$ is approximately equal to C_{L0}^2 , the lift coefficient at 0° yaw.

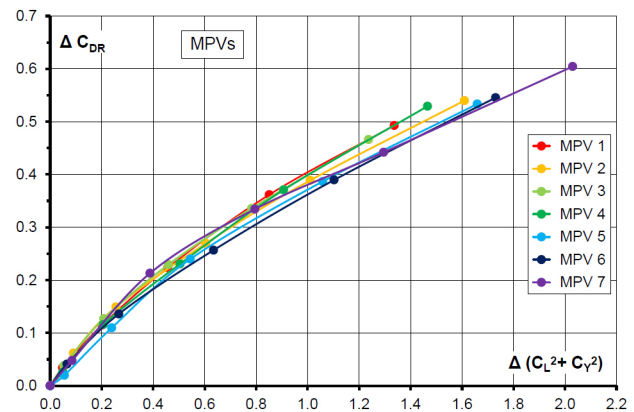


Figure 2(a). Wind axis drag as a function of lift and side force for a range of MPVs.

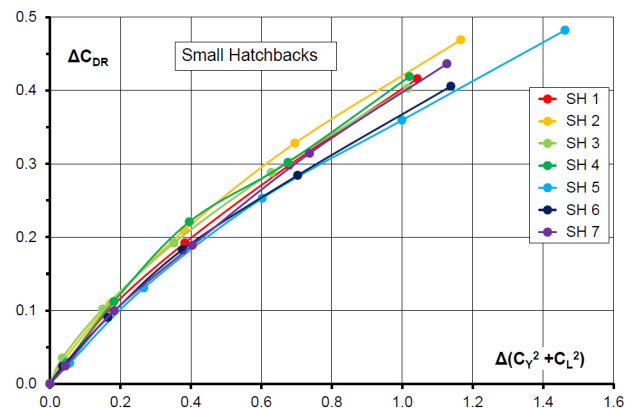


Figure 2(b). Wind axis drag as a function of lift and side force for a range of small hatchbacks.

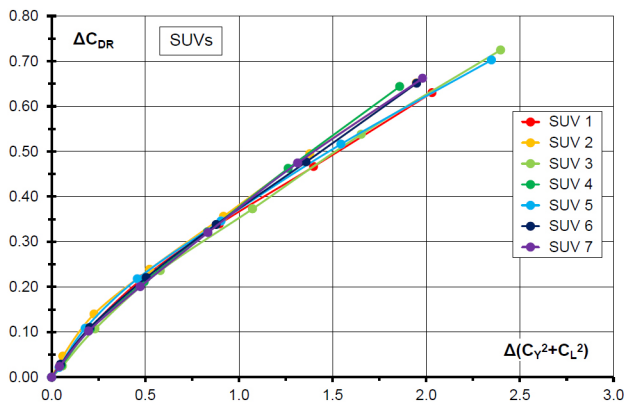


Figure 2(c). Wind axis drag as a function of lift and side force for a range of SUVs.

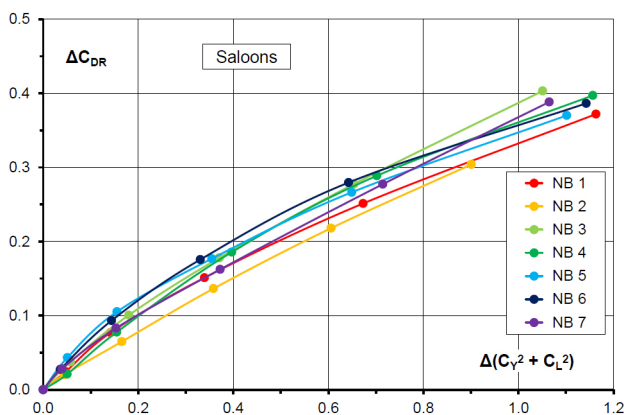


Figure 2(d). Wind axis drag as a function of lift and side force for a range of saloon cars.

It should be noted that, in Figure 2, both the vertical and horizontal axis scales shown vary significantly for the different vehicle categories.

While the drag variation with yaw is considerable the wind axis drag data is shown to be very similar for the range of cars in a given category. The exception is the saloon car category where there is a noticeable variation in the drag characteristics. For clarity the data of Figure 2 shows positive yaw angles only. The maximum yaw angle shown is 25°, but the approximately linear range at higher yaw angles extends beyond a yaw angle of 30°.

DISCUSSION

Given the very wide range of drag characteristics shown in Figure 1, it is remarkable that the wind axis drag data should in most cases be very consistent. The collated data for all the vehicles from the different categories is shown in Figure 3, where only the different categories are identified.

The data shown in Figure 3 suggests that the wind axis drag is primarily a function of lift and side force only and the relationship is, remarkably, close to universal. As this drag component is also a function of drag in the standard body axis, as normally measured, and side force, then the increase in the normal drag coefficient is itself only a function of side force and lift.

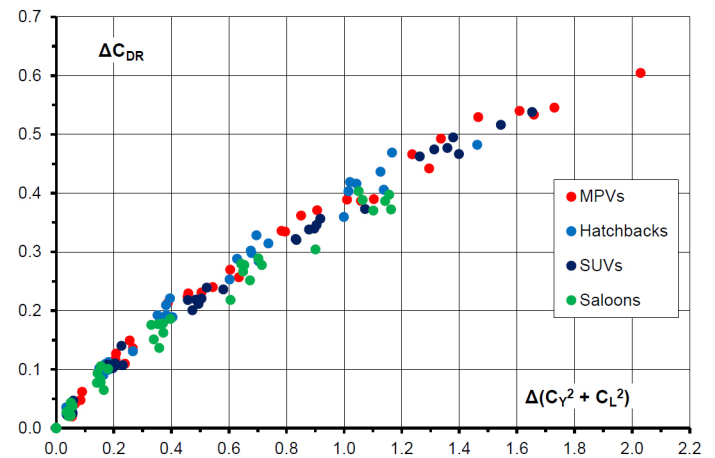


Figure 3. Wind axis drag as a function of lift and side force for all cars.

Side Force

The variation of side force with yaw angle for a given vehicle type are, however, also known to be very similar. The data for the different vehicle categories investigated in this paper are shown in Figures 4(a), (b), (c), (d).

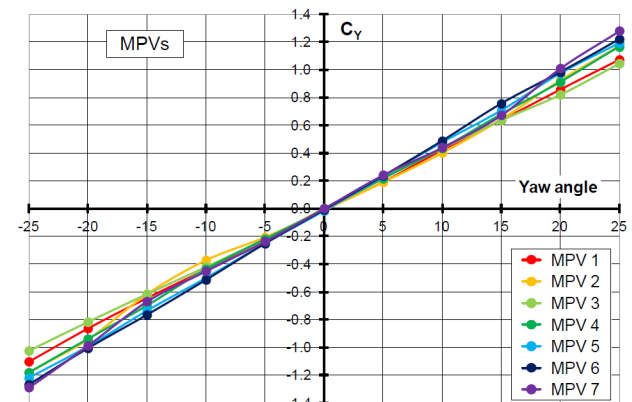


Figure 4(a). Side force variation with yaw for a range of MPVs.

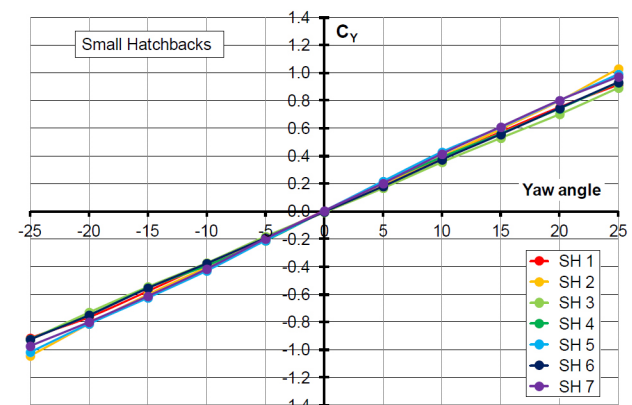


Figure 4(b). Side force variation with yaw for a range of small hatchbacks.