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Streamlined Tails – The Effects of Truncation on Aerodynamic Drag

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Abstract

Significant aerodynamic drag reduction is obtained on a bluff body by tapering the rear body. In the 1930's it was found that a practical low drag car body could be achieved by cutting off the tail of a streamlined shape. The rear end of a car with a truncated tail is commonly referred to as a Kamm back. It has often been interpreted as implying that the drag of this type of body is almost the same as that for a fully streamlined shape. From a review of the limited research into truncated streamlined tails it is shown in this paper that, while true for some near axisymmetric bodies, it is not the case for many more car-like shapes. For these shapes the drag reduction from an elongated tail varies almost linearly with the reduction in cross section area. A CFD simulation to determine the drag reduction from a truncated streamlined tail of variable length on the simple Windsor Body is shown by way of confirmation.

Introduction

In the 1920's and 30's the concept of streamlining took hold of the public imagination and was applied to all forms of transportation, including cars, [1]. At the forefront of this early development was Paul Jaray, who had worked on car shapes in the Zeppelin wind tunnel. At the time the epitome of a low drag shape was represented by the airship, but Jaray recognised that close to the ground an upper half-body shape was more appropriate. Jaray later introduced a composite streamlined body with a half-body streamlined cabin added onto a streamlined pontoon body. Various cars were produced which demonstrated both these approaches to a low drag automobile. In all cases the aim was to have a fully streamlined tail. As these cars typically had rear mounted engines they were inherently compromised for stability especially in crosswind conditions and they were also impractical because they were so long. (For a comprehensive review of the early history of car aerodynamics the reader is referred to Hucho, [2],(or Schütz, [3],) and Ludvigsen, [4]).

In the mid 1930's, however, it was shown by different German aerodynamicists that by cutting off the tail, the problems of stability and impracticality would be reduced and low drag could still be achieved. Comparable drag was obtained if the elongated tail was truncated at the point where flow separation was likely to occur. This major development is generally credited to Kamm, working at FKFS, but his co-worker Koenig-Fachsenfeld and Everling at Berlin

University have competing claims for this breakthrough in car design, which is known as the K-Back (and often as the Kamm-back). The issue is discussed by Hucho, [2], but is unresolved. An extensive review of the research into car aerodynamics conducted in Germany during the 1930's can be found in Koenig-Fachsenfeld, [6]. At this time Kamm developed four prototype cars, K-1 to K-4, to promote the idea; one of which, K-2, survives.

In 'Aerodynamics of Road Vehicles' edited by Hucho (4th edition), [2], and Schütz (5th edition), [3], the investigation by Mair on drag reduction of axisymmetric bodies with boat-tailing is cited as confirmation of the K-back effect, whereby the drag penalty from truncating a streamlined tail is negligible. While this data certainly shows that the drag reduction from a streamlined tail is closely matched by a significantly truncated tail, it is questionable that an axisymmetric body is representative of typical car shapes. The validity of this claim for car shapes is assessed in this paper by reviewing the published information.

It is remarkable, however, how little data is available on the effects of streamlined tails on non-axisymmetric bodies, whether representative of road vehicles or not. In the absence of a significant database a basic CFD simulation has been undertaken to determine the effects of adding an extended tail to the simple Windsor body to create an almost fully streamlined tail, which is then truncated in steps. The results are presented in this paper and an attempt made to correlate the available information. The data is compared with a study of the effects of the development of rear body tapering on simple squareback shapes to provide some context.

Historical Data

For this paper, historical data refers to data obtained in the early days of vehicle aerodynamics research, during the 1920's and 1930's. As early as 1921, Klemperer, while working for Jaray at the Zeppelin Works, showed in drag measurements on a body with a square cross-section, reported by Ludvigsen, [4], that drag was substantially reduced by a streamlined tail, provided that the body had a well-rounded front end and the benefit was enhanced if the tail was tapered on all sides.

In 1932, Professor Lay at the University of Michigan carried out the first systematic investigation into the effects of front and rear shapes

on the drag of simple bodies representing automobiles, [5]. The body shapes are shown in Figure 1, and the principal dimensions are given in Table 1. The effect of tail length on the drag coefficient is shown as a function of tail length in Figure 2. Hucho, [2], has commented that the shapes tested look odd today, and also, that the drag data, which was presented differently to that shown in Figure 2, suggests that a long tail is not necessary. It can be noted, however, that there is a substantial drag benefit from the tail, although the trend to a streamlined tail was not measured. The drag reduction is a function of the front end shape and tends to increase as the front end drag reduces. Front end C represents the well-rounded front, while front ends D to F incorporate windshields with increasing bluntness. The upper taper angle for the streamlined tail is approximately 19° and the side taper angles are 11.3° . The Reynolds Number, based on body height was 4.3×10^5 ; (2.4×10^6 based on maximum length).

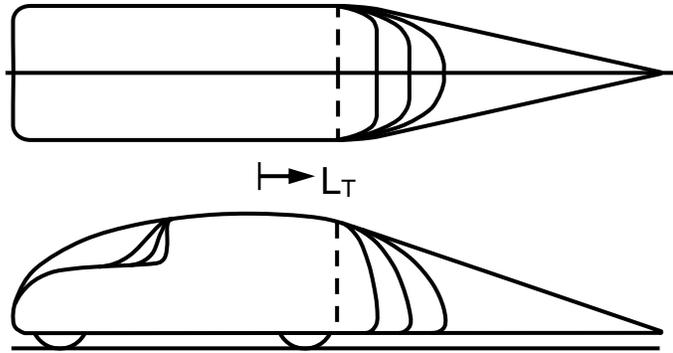


Figure 1. Lay models.

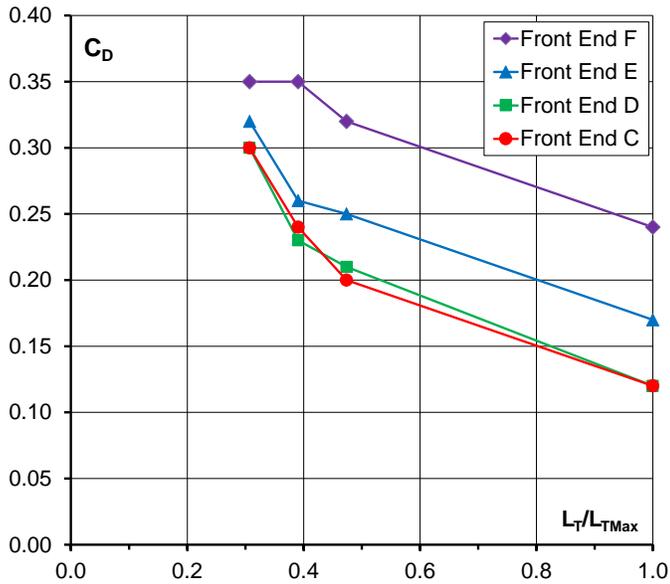


Figure 2. Drag coefficient reduction with tail length for the Lay models.

Some slightly later experiments, conducted at FKFS, as reported by Koenig-Fachsenfeld, [6], compared J-back, curved style, and K-back, square style, base configurations on a streamlined shape as shown in Figure 3. Both bodies had a rectangular cross section with sharp side edges.

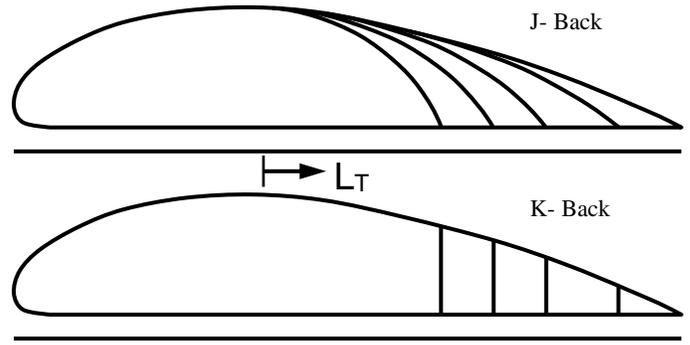


Figure 3. FKFS models.

The drag coefficient data, reproduced in Figure 4, with the different geometries, showed the superiority of the K-back configuration in limiting the drag increase from truncating the tail. The higher drag for the J-back configurations was the result of increased suction on the highly curved upper rear surface and a higher vortex drag component from the steeper upper side edges.

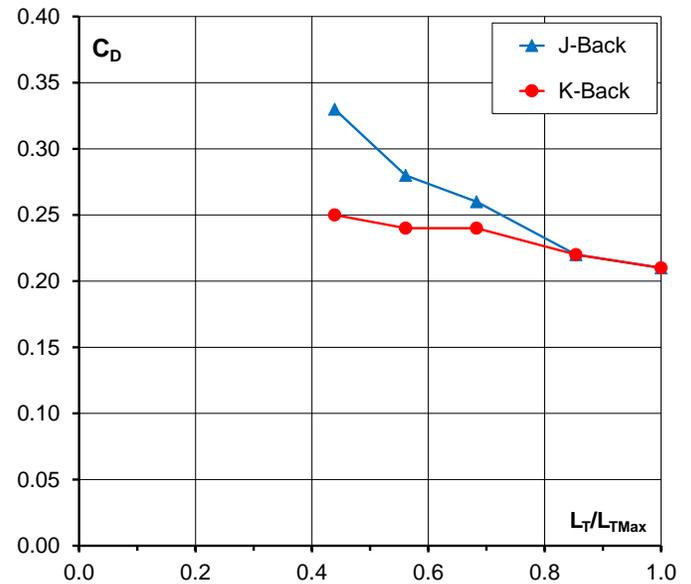


Figure 4. Drag reduction with tail length for the FKFS models.

The principal dimensions of the Lay and FKFS bodies are given in Table 1. The length and height are the maximum dimensions.

Table 1. Principal details of Lay and FKFS bodies.

Reference	Body Dimensions (m)		
	L	H	W
Lay [5]	1.137	0.203	0.229
FKFS [6]	0.64	0.16	0.22

In [6] it was also shown that the side profiles of the Lay and FKFS streamlined bodies were very similar, although the taper angle for the FKFS model varies along the length of the tail and at the trailing edge is approximately 26° based on the sketches. The plan shapes were, however, different with the FKFS bodies having a rectangular

planform and the Lay bodies having tails with tapering on the top and sides. It was concluded by Koenig-Fachsenfeld, [6], that the K-Tail gives almost the same drag as a fully streamlined tail.

Comparison of the two studies shows that the overall drag reduction is considerably greater in the Lay experiment than in the FKFS study. Some of this will result from the rounder edges on Lay's model, but the tapering of the tail in plan and side view will also have an effect, by inhibiting vortex formation on the side edges.

Streamlined Tails Survey

Axi-symmetric Bodies

The contention that a truncated streamlined shape can have almost the same drag as a fully streamlined body is supported by the experimental studies by Mair, [7], for the effects of boat-tailing on a long axi-symmetric body, and Wong and Mair, [8], for tapered after-bodies on a square section body. In the former case, different boat-tail configurations were tested and the data from two of those configurations are shown here. In one case the tail was extended into a conical surface with a semi-cone angle of 22° to generate an almost fully streamlined configuration and the transition from the cylindrical main body to the conical tail was a sine curve. For the other case an ellipsoidal afterbody with the major/minor axis ratio of 1.67 was added. For the square section body the data for the tail with taper angles of 20° on all four sides is shown here. The bodies tested are shown in Figure 5. The diameter of the axi-symmetric body and the side of the square section body, D' , was, in both cases, 0.152 m.

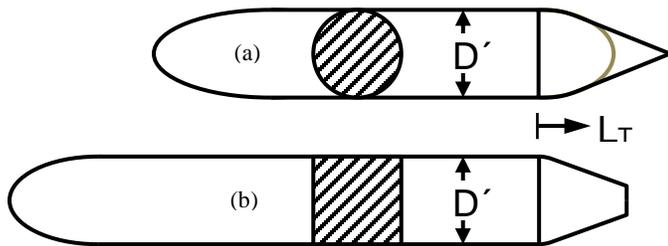


Figure 5. Axi-symmetric body (a) with ellipsoidal and conical tails and square section body (b) with straight tapered tail as tested by Mair,[7], and Wong and Mair, [8], respectively.

The forebody in all cases was ellipsoidal, although the square section body had a shorter major axis than the axi-symmetric body. All the afterbodies were constructed of multiple sections to allow the tails to be truncated. The effects of tail length on drag reduction for the three different bodies is presented in Figure 6. The drag has only been obtained on the afterbody, so the drag data is presented as the change in drag coefficient from the blunt base configuration. It should be noted that the data for the conical tail on the axi-symmetric body and the tapered tail on the square section body do not extend to the fully streamlined case. In the former case the fully streamlined tail has a L_T/D' ratio of 1.5, while in the latter case the L_T/D' ratio is 1.37. For the three cases shown in Figure 6 the drag coefficient reduction is within 0.003 of the maximum when the base area is approximately 50% of the frontal area.

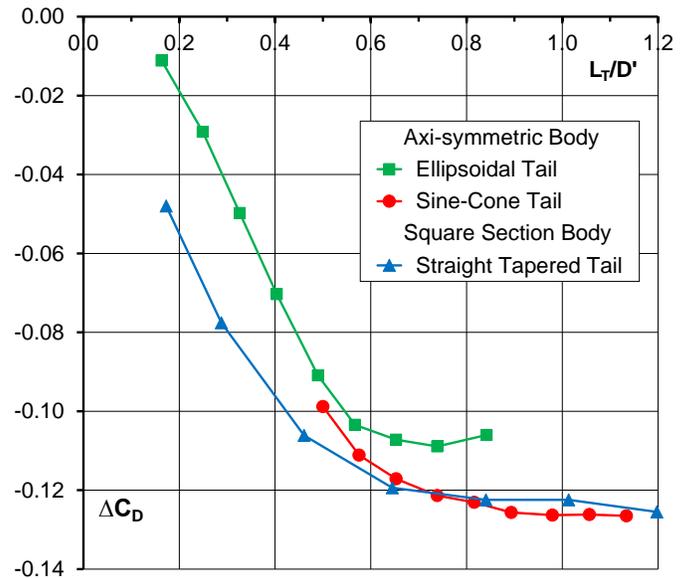


Figure 6. Drag reduction from extending the tails of the bodies shown in Figure 5.

The drag reduction from rear body tapering on axi-symmetric bodies that include a full taper has been measured by, amongst others, Heinrich and Eckstrom, [9], and Compton, [10]. The bodies are shown in Figure 7. For both cases there was no transition from the cylindrical main body to the conical afterbody. For reference [9] the forebody was ellipsoidal while in reference [10] the forebody was conical and only the drag of the rear body was measured. The drag reduction as the tail length is increased for both bodies is shown in Figure 8. These axi-symmetric cases with conical afterbodies had various cone angles and were tested at different Reynolds numbers.

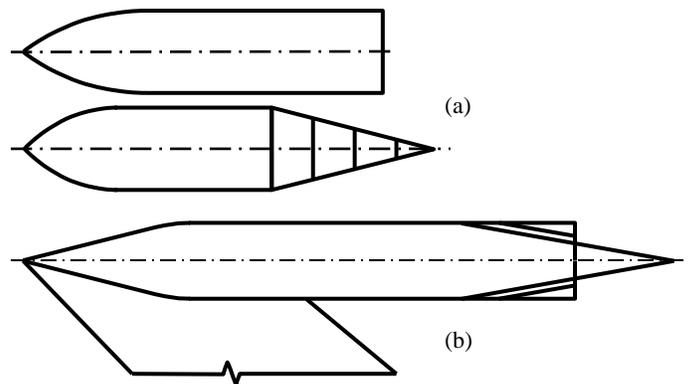


Figure 7. The axisymmetric bodies with truncated tails tested by Heinrich and Eckstrom, [9], shown (a), and by Compton, [10], shown (b).

Table 2. Principal details of axi-symmetric bodies with conical afterbodies.

Reference	Body Diameter D' (m)	L'/D'	Taper Angle $^\circ$	$R_{cD} \times 10^6$	$R_{cL} \times 10^6$
Mair [7]	0.152	4.35	22	0.46	4.00
Heinrich et al [9]	0.152	3/4.5	~ 14.3	0.23	1.04
Compton [10]	0.038	7.8	10	1.06	8.27

The principal characteristics for the different axi-symmetric bodies with conical afterbodies as shown in Figure 7 and Figure 5(a) are given in Table 2. The body length, L' , used to generate the length to diameter ratio, L'/D' , is given for the blunt base case.

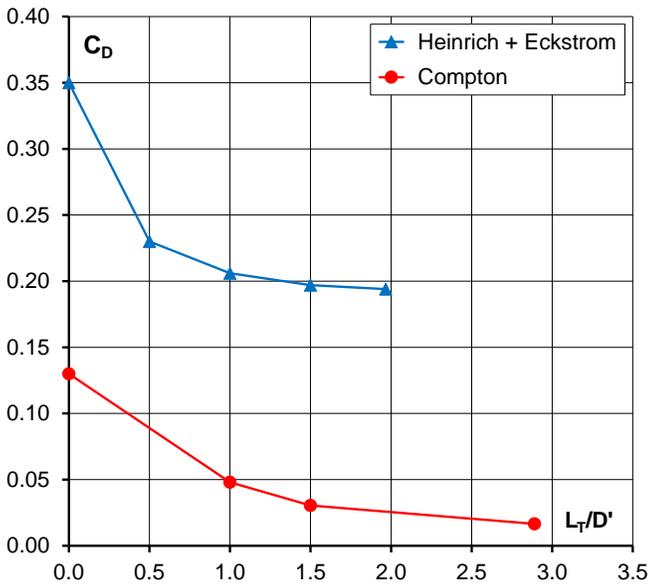


Figure 8. Drag reduction from streamlined tails shown in Figure 7.

Hoehner, [11], has shown that base drag is a function of forebody drag, and on this assumption predicted that the drag increase from truncating the trailing edge of a streamlined axisymmetric body increased as the cube of the diameter and was simply given by:

$$\Delta C_D = f(D'_B/D'_M)^3 \quad (1)$$

where D'_B is the diameter of the truncated base and D'_M is the maximum diameter of the body. The two axisymmetric bodies shown in Figure 7 demonstrate this relationship almost exactly for base diameter ratios up to 70%.

Wheelless Bodies

There have been very few studies of the effects of a streamlined tail on low drag bodies. Stollery and Burns, [12], truncated the tail of a streamlined body shown in Figure 9(a). The principal dimensions are given in Table 3. The maximum thickness is at 23.3% of the length. The planform shape of the body is rectangular with a semi-circular nose. The taper angle of the tail is 10.5° on both upper and lower surfaces. The drag increase as the tail length is reduced, for the body in free stream, is shown in Figure 10. Data obtained in ground proximity with ground clearances of 0.025 m and 0.045 m shows that the drag increase with truncation is reduced but the trend is not available.

Table 3. Principal details of the bodies tested by Stollery & Burns, [12], and Onorato et al., [13].

Reference	Body Dimensions (m)		
	L'	H	W
Stollery & Burns [12]	1.092	0.229	0.381
Onorato et al [13]	1.260	0.275	0.495

Onorato et al., [13], have also tested a low drag body with a truncated streamlined tail in ground proximity. The body, without wheels, is shown in Figure 9(b). The principal dimensions are given in Table 3. The ground clearance is 0.047 m and the maximum thickness is at approximately 35% of the length. The effective included (upper + lower) taper angle over the rear section of the tail is 26° , although this is cambered. The tail is highly tapered in plan view and the plan profile follows the upper body side profile, but the plan shape of the trailing edge cannot be deduced from the published drawings.

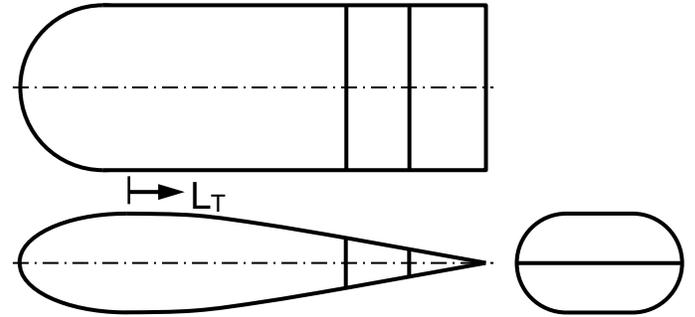


Figure 9(a). Truncated body tested by Stollery and Burns, [12].

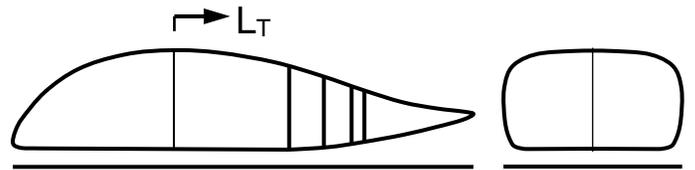


Figure 9(b). Truncated body tested by Onorato et al., [13].

The increase in drag coefficient as the tail is progressively removed is shown in Figure 10. Modifying the front end to simulate a windscreen only increased the drag coefficient of the fully streamlined body by $\Delta C_D = 0.003$; a similar result to that found by Lay, [5].

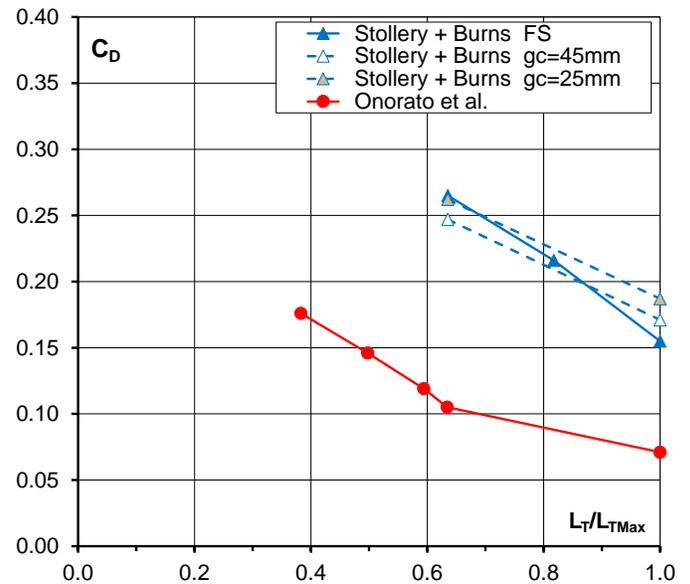


Figure 10. Drag reduction from streamlined tails shown in Figure 9.

Additional Studies

Howell, [14], in a study of the aerodynamics of magnetically levitated high speed trains, added a streamlined tail in two sections to a blunt based body with a low drag forebody, as shown in Figure 11. The overall length of the main body was 0.57 m; the truncated tail section was 0.10 m long while the streamlined tail added a further 0.15 m. The cross section consisted of a rectangular lower part and a semicircular upper body giving a height and width of 0.112 m. The taper angle on roof and sides was 15°. The width at the trailing edge of the streamlined tail was 0.006 m. The ground clearance was 0.012 m and the Reynolds number for the test was 2.0×10^5 , based on body width and 1.0×10^6 based on the blunt body length. The drag reduction from adding the tail is shown in Figure 13.

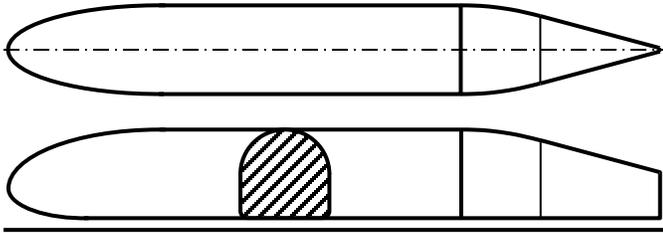


Figure 11. Maglev train model tested by Howell, [14].

Götz, [15], added a tapered extension to the base of a bluff body representing a truck or coach. The ‘rectangular’ body had no wheels and a smooth underfloor. The tapering was applied to the upper surface and sides of the tail, as shown in Figure 12, and was extended to create a fully streamlined tail. The taper angles on both roof and body sides, based on the drawings in reference 15, are taken to be 15°. The dimensions of the body are, unfortunately, not known.

The drag reduction from adding the tail, estimated from reference [15], is shown in Figure 14, for the body with a radiused front end (top and side edges only). The body was also tested with all leading edges sharp. In this case the overall drag was much higher, but the drag reduction from adding the tail was increased by approximately 10%.

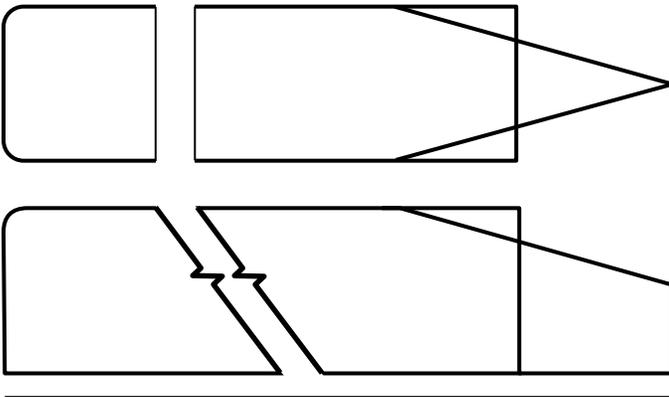


Figure 12. Simple shape representing a truck as tested by Götz, [15].

A highly streamlined truck has been developed by MAN; the Concept S, where the elongated tapered tail provides the same internal volume as the standard box shaped container. The tapering was done in two stages; initially on the roof only and then on roof and rear sides. As reported in Schültz, [3], the truck length exceeds current limits but a

drag coefficient of 0.3 is achieved. The truck shapes are shown in Figure 13 and the effects on the drag coefficient of tapering the tail are shown in Figure 14. For comparison purposes, the maximum tail length is set by arbitrarily extending the side profile of the low drag configuration to produce a nominally fully streamlined configuration.

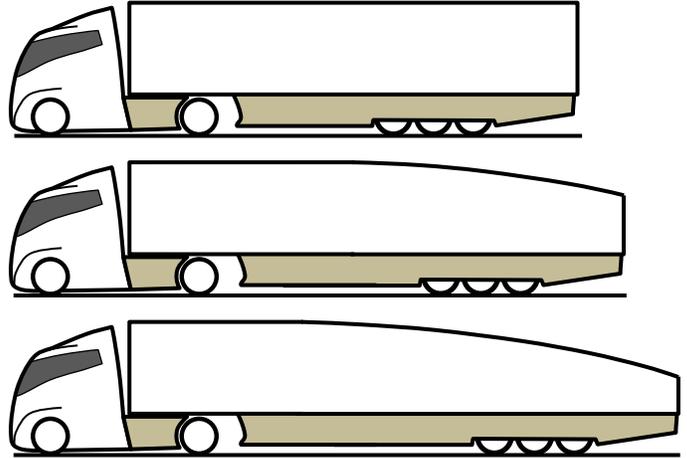


Figure 13. MAN Concept S Streamlined truck.

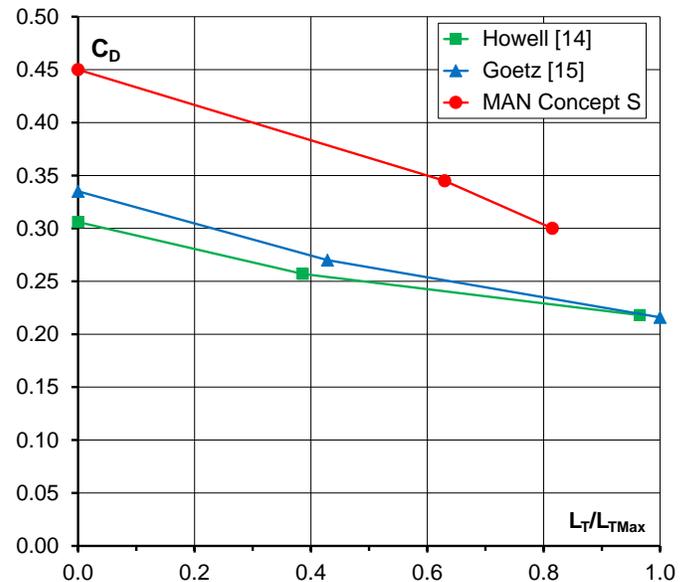


Figure 14. Drag reduction from streamlined tails on trucks and a high speed train model.

Nakaguchi, [16], added an ellipsoidal tail to a long body representing a truck. The body had a square cross section and three front ends, which could be spaced from the main body to represent a tractor-trailer combination. The bodies, which were tested in ground proximity, are shown in Figure 15 with no gap. The front ends are shown as an ellipsoidal shape, A; a bluff sharp edged form, C, and an intermediate configuration, B.

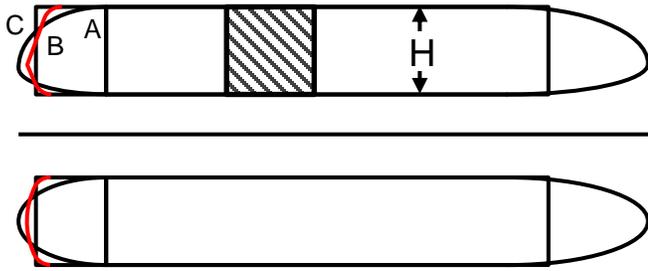


Figure 15. Simple bodies tested by Nakaguchi, [16].

The ellipsoidal nose section length was equal to the body height, H , while the elongated tail was $1.6H$. The Reynolds Number based on body width was only 1.6×10^5 and was 1.15×10^6 , based on the longest body length. The ground clearance was $0.45H$. The bodies were not tested in truncated form, but the drag coefficients for the bodies shown, as estimated from [16], are given in Table 4.

Table 4. Drag Coefficient data for the bodies tested by Nakaguchi, [16].

Front End	Rear End	L/H	C_D	ΔC_D
Ellipsoidal, A	Square	6.05	0.31	-
	Ellipsoidal	7.18	0.21	0.10
Intermediate, B	Square	5.95	0.45	-
	Ellipsoidal	7.08	0.36	0.09
Sharp, C	Square	5.85	0.90	-
	Ellipsoidal	6.98	0.77	0.13

For the two bodies where the front end flow is attached, front-ends A and B, the drag benefit from adding the ellipsoidal tail is reduced when the front end drag is increased by the intermediate nose shape, although the overall drag is increased. The sharp edged nose shape, however, has significantly higher overall drag, but the drag benefit from the tail is greater, which is a similar finding to Götz, [15].

There are a few types of vehicle that have streamlined tails as standard. These are either machines of extreme efficiency, such as solar race cars, mileage marathon cars and HPVs (Human Powered Vehicles), or extreme speed such as speed record breakers. In this latter category the aerodynamic development of the Mercedes-Benz 111 series has been reported by Götz, [17]. The effect of a fully streamlined tail on the M-B C111/3 vehicle was obtained from wind tunnel tests using 1:10 scale models. The extended tail is shown in Figure 16. It is assumed that the rear body sides aft of the rear wheels were tapered slightly as on the final vehicle. The drag reduction with tail length is given in Figure 17 as a ratio of the initial drag coefficient without the extended tail. The final vehicle length of 5.38 m is indicated on the plot.

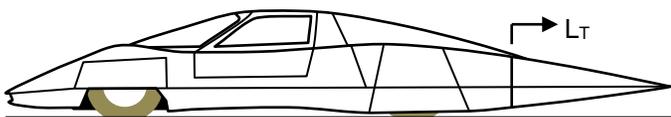


Figure 16. Mercedes-Benz C111/3 with streamlined tail.

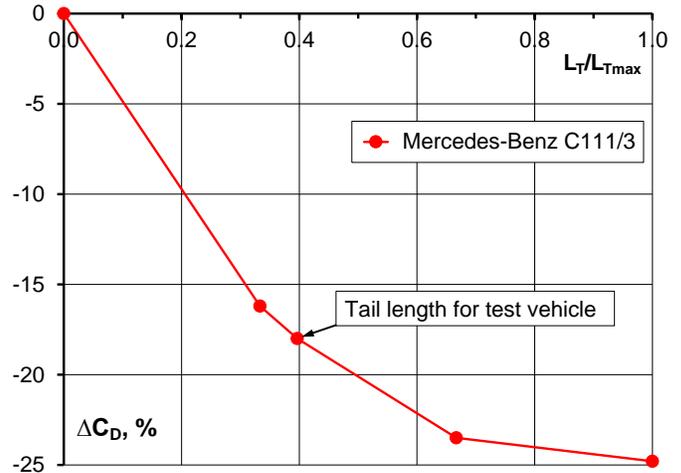


Figure 17. Drag reduction from an extended tail on the M-B C111/3 model.

CFD Simulation

The review of the available data on streamlined tails has shown that a reasonable amount of data exists, on many different types of bodies. While only some are representative of car geometries, very few contain more than a couple of truncated configurations or have been conducted systematically. This makes it difficult to establish trends. It was decided, therefore, to carry out a basic CFD simulation to address some of these issues.

The simulation was based on the Windsor body as this basic shape has been used extensively at Loughborough University for experimental and CFD investigations and wind tunnel data exists for the body with a range of slant aspect ratios. The standard squareback body and the body with a streamlined tail are shown in Figure 18. The squareback model is 1.044 m long by 0.389 m wide and 0.289 m high. The ground clearance in all cases is 0.050 m.

The taper angle on the streamlined tail is 12.5° and the taper is initiated 0.310 m upstream of the base of the squareback model and the tail is extended beyond the squareback model base in 5 sections, each of which is 0.17 m long. The trailing edge of the final configuration is 0.032 m deep. An additional taper length of 0.217 m was also investigated. This configuration has a slant length of 0.222 m which is the standard slant length for the MIRA wind tunnel experiments, [18], on the Windsor body.

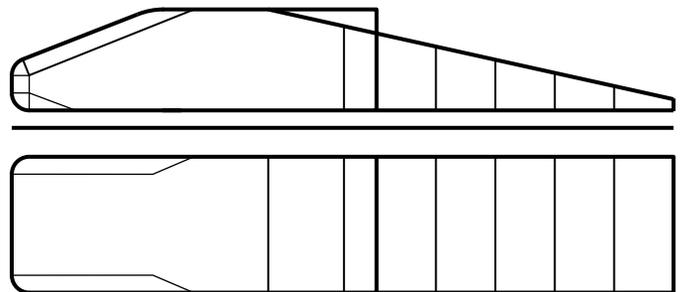


Figure 18. Windsor Body with streamlined tail.

For the CFD simulation the Windsor body is positioned in a domain of length 7.83 m (7.5L), width, 1.92 m (4.9W), and height, 1.32 m (4.6H), where L, W, H are the length, width and height of the Windsor Body in squareback form. The inlet length upstream of the body is 1.57 m (1.5L) and the downstream length is 5.22 m (5L) for the squareback case. The cross section matches the Loughborough University wind tunnel working section dimensions. A hexahedral mesh is applied with the highest refinement close to the body as shown in Figure 19. The total number of volume elements is approximately 14×10^6 . The smallest elements on the body surface were 10^{-5} m thick to satisfactorily resolve the boundary layer viscous sublayer. No slip conditions are applied at the walls. The simulations were performed using the STAR-CCM+ software v10.4.009 from CD-Adapco. A RANS two equation $k-\omega$ SST (Menter's Shear Stress Transport) turbulence model is used. All simulations were run for 5000 iterations which produced convergence in all cases. The blockage is 4.4% and corrections are applied to the forces and pressures generated using the MIRA (continuity) method.

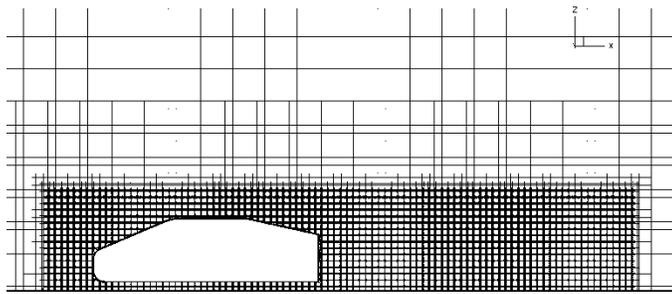


Figure 19. Mesh details for the CFD domain close to the Windsor body.

The pressure distribution on the slanted surface and the base of the Windsor body, as predicted by the CFD simulation, are shown in Figure 20 as the tail length increases from the squareback geometry to the near fully tapered case, while the drag and lift coefficients for the same cases are shown in Figure 21. The baseline drag and lift coefficients and the mean base pressure for the squareback configuration are given in Table 5.

Table 5. Coefficients for squareback Windsor Body.

	C_D	C_L	C_{PB}
CFD simulation	0.233	-0.065	-0.167
Wind tunnel	0.262	-0.138	-0.177

The pressure distributions presented in Figure 20 show there is a pronounced suction at the leading edge of the slant in all cases. For the shorter slant lengths the pressure on the central region of the slanted surface increases rapidly along the length of the slant and a strong suction forms along the side edges of the slant. As the length of the taper increases the pressure along the centreline becomes positive and the transverse pressure distribution is more uniform as the trailing edge is approached.

The suction on the side edges of the shorter slant lengths indicates strong edge vortices, but as the taper length increases these do not appear to continue growing. It can be seen that the pressure distribution on the slanted surface up to the point of separation on the truncated body is approximately the same as that occurring on the same surface of the tapered body of maximum length.

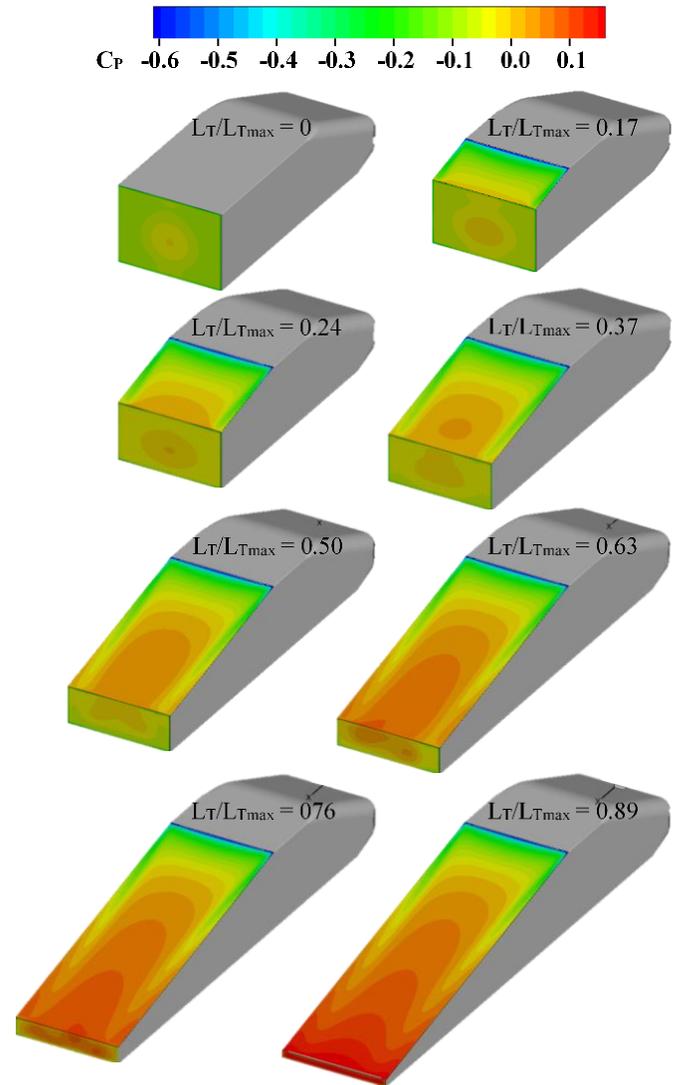


Figure 20. The pressure distribution on the slant surface and base of the Windsor Body.

Figure 21 shows the development of the drag and lift forces on the Windsor body as the tail length is increased. The slant and base drag components contributing to the overall drag are included. All the data is shown as a change from the squareback configuration.

The drag on the slanted surface is shown to initially increase with taper length but at a length of 0.6m becomes approximately constant, which suggests no increase in the vortex drag component. The mean base pressure increases as the base area reduces and becomes positive on the base of the body with the longest tail. The base drag reduces almost linearly as the taper length increases. Also shown is the drag increase arising from the skin friction, which is seen to be small but grow constantly with length. There is some double counting here as the slant drag component also includes the local skin friction. The net result on total drag shows a continuous reduction with tail length with an increased and constant rate of change for the longer tails. Lift, however, increases continuously, but generally slowly, with taper length.

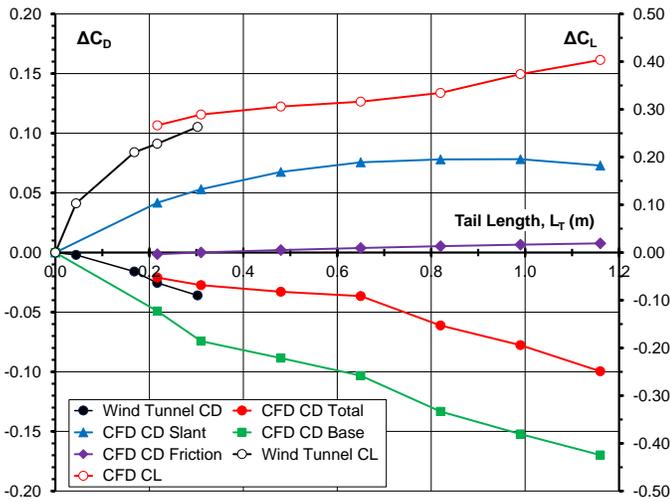


Figure 21. Comparison of Wind Tunnel and CFD data for the increase in lift and drag coefficient from roof tapering on the Windsor Body. The wind tunnel data is interpolated from the data shown in Figure 22.

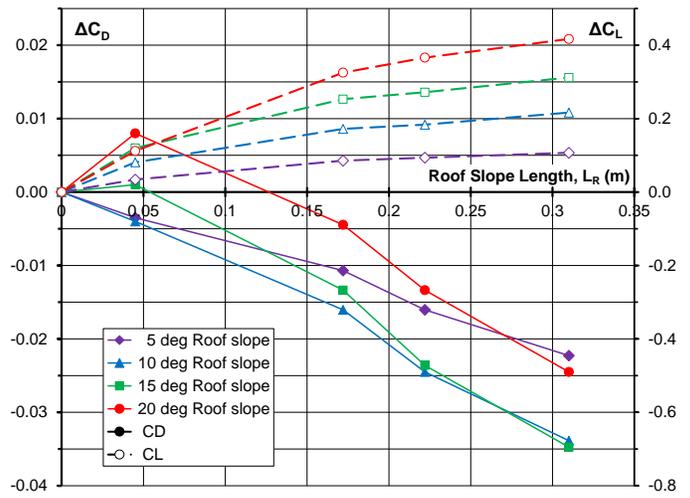


Figure 22. Effect of roof tapering on drag and lift for the Windsor Body.

The CFD data in Figure 21 is compared with the limited wind tunnel data for the Windsor body with shorter tapered rear ends, as discussed in the following section.

Discussion

Tapered Windsor Bodies

There is no experimental data for the drag reduction from a fully streamlined tail on the Windsor Body for comparison with the CFD results. However, some data is available for the effects of changing slant angle length to vary the aspect ratio of the rear body slant. Howell and Le Good, [18], explored drag and lift characteristics for a range of slant aspect ratios from 1.25 to 2.25, while Pavia, [19], obtained data for a short trailing edge chamfer, which had a slant aspect ratio of 8.64. It should be noted that in each case the aspect ratio of the slanted surface was kept constant. There was no bodyside tapering, so the data is consistent with the CFD simulation. The former experiment was conducted in the MIRA MWT. In the latter case the test was in the Loughborough University WT and the data is interpolated for a consistent set of roof taper angles.

The effect of slant length on drag reduction and lift increase for different slant angles is shown in Figure 22. For the smallest slant length the drag reduction from the squareback configuration occurs only for slant angles less than approximately 14°. For the longer slant lengths the drag reduces approximately linearly with length. The data is corrected for blockage using the standard MIRA correction method.

For comparison with the results of the CFD investigation the experimental data given in Figure 22 is interpolated to generate drag and lift coefficients for a slant angle of 12.5° and is shown in Figure 21 as a function of tail length. The data is presented as the difference in the drag or lift coefficient for the body with a roof slant from the squareback case.

MIRA Reference Car

There is almost no experimental data for highly tapered rear ends on car-like shapes, where the tapering is applied on the body sides as well as the roof, although Ludwig, reported in [20], has shown substantial benefits due to the suppression of the slant edge vortices. Howell et al, [21], have reported on two sets of experiments that investigated the effects of rear upper body tapering. One was conducted on the Windsor Body model with short tapers and the other was carried out using the full scale MIRA Reference Car with a longer tapered section. A sketch of the MIRA Reference Car with a representative tapered rear end configuration is shown in Figure 23. The reference car is a simplified car shape with extensive flat surfaces. It has a smooth underfloor and no cooling flow. The wheels are shrouded. The car is 4.18m long, 1.625m wide and 1.42m high. The ground clearance is 0.20m. An edge radius of 0.15m is applied to the leading and longitudinal edges, but the trailing edges are square. The rear underfloor has a diffuser angle of 10°. The length of the rear taper section is 1.33m. The Reynold's Number based on body height was 2.26×10^6 and 7.96×10^6 , based on the length.

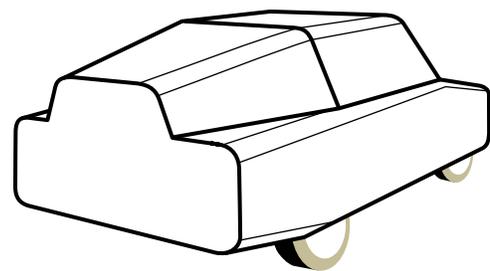


Figure 23. MIRA Reference Car with rear end tapering.

The MIRA Reference Car is normally used in three configurations representing saloon, estate and fastback vehicles. For the experiment reported here it was modified with customised rear end tapering of the roof and upper bodysides. In Figure 24 the drag reduction data from reference 21 is replotted as a function of base area. The drag reduction is relative to the standard squareback (estate) configuration and is shown for side taper angles from 0° (straight) to 15° for roof angles varying from 0° to 15°. (20° for the 0° side taper).

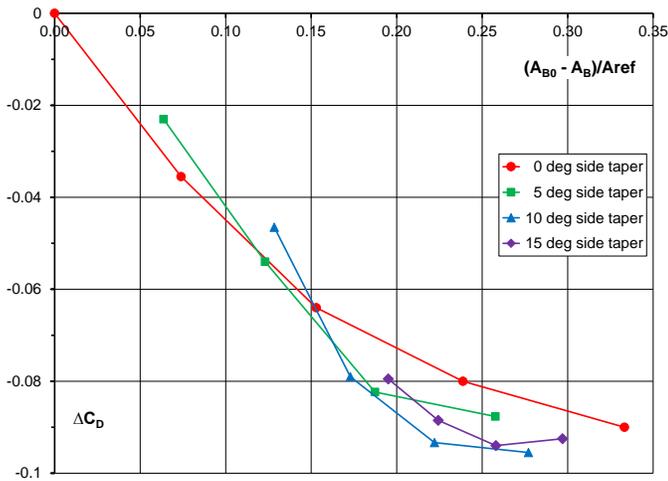


Figure 24. Drag reduction from rear end tapering on the MIRA Reference Car.

It can be seen that moderate side tapering enhances the drag reduction obtained with roof tapering alone, but the benefit is small, and it is interesting to note that with roof and bodyside tapering the drag reduction is a function of base area only. Howell and Le Good, [18], showed that, with short tapers, the base drag reduction was a function of base area. For longer tapers, however, all the drag reduction arises from the base, as shown in Figure 21, and so the overall drag reduction becomes a function of base area.

Streamlined tails

The data presented in the Streamlined Tails Survey on the drag benefit from streamlined tails is highly variable, which is to be expected from a series of independent tests conducted over a long period. The streamlined tails have different taper angles and are attached to a range of forebody shapes; some have wheels and some are basic bodies with different ground clearances; and the tests have been conducted at different Reynolds Numbers, (Re).

The variability in Re and forebody shape introduces a significant complexity in that the drag reduction resulting from the base pressure recovery, which is a consequence of the tapering, is dependent on the base drag of the untapered and blunt-base body. Thus a test conducted at low Reynolds number on a body with a moderately bluff forebody (but without any flow separation) and a squareback rear end will have a low base drag in comparison with a body that has a low drag forebody at high Re. This is a consequence of the thicker boundary layer at the body trailing edge and a thicker separated shear layer which produces a higher base pressure, as discussed by Hoerner, [11]. Under these conditions the potential for drag reduction from rear body tapering or a streamlined tail is reduced. This effect is demonstrated in the results from both Lay, [5], and Nakaguchi, [16].

From the results of Hoerner, [11], given by equation (1) for an axisymmetric body and supported by the data presented in Figure 24 it is assumed that the drag increase that arises from truncating a streamlined tail will be some function of base area. In Figure 25 the drag increase is presented as a function of the increase in base area from a fully tapered configuration. Both drag increase and base area are non-dimensionalised by the values for a base area equal to half the frontal area.

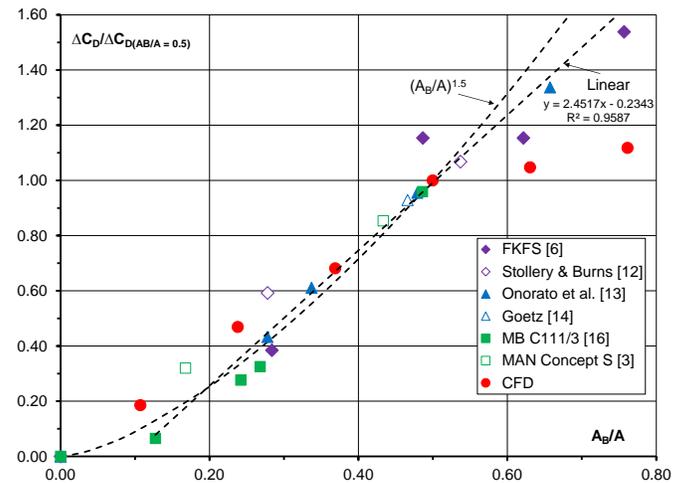


Figure 25. Drag increase from a truncated streamlined tail.

For references [3], [13], [15] and [17] the area ratios are estimated based on the drawings available. This introduces a degree of uncertainty in determination of the area ratios as the drawings can be small scale and of unverifiable accuracy. All the experimental cases, with the exception of the Concept S truck, have data which includes the fully streamlined tail. For the truck case the streamlined tail configuration is estimated by extrapolating the area ratio to zero using a polynomial fit to the available data. The Lay experiment is not included as the truncated bodies have well rounded edges such that the base areas cannot be readily defined and the longest truncated case is outside the scope of the graph.

The CFD data supports the linear relationship between drag increase and area ratio up to an area ratio of 0.5, but at higher area ratios, (ie for shorter tapered bodies), the CFD data shows a reduced drag increase, which diverges markedly from the limited experimental data.

It can be seen that the trend of the data suggests a linear relationship, although the trendline for the data excluding the fully streamlined configurations is slightly offset from zero. A reasonable case could also be made for the drag increase to be a function of $(A_B/A)^{1.5}$, as derived by Hoerner, [11], and as shown in Figure 25. Although the total data is scarce the graph could further suggest that the linear relationship applies to the bodies without platform tapering, and the power law is applicable to the bodies with tapering in both plan and side view.

K-Back

The sharp edged truncated rear body on notchback and fastback cars is commonly referred to as a Kamm-tail, named after Professor Kamm. While Kamm was a strong and, probably the most influential, advocate of the short bluff rear end shape of cars, he was not the only one and others claim that distinction, as mentioned in the Introduction. As discussed by Hucho, [2] these events occurred too long ago to be resolved now. However, some observations may be relevant.

Kamm's research was conducted at a time when most cars which aspired to have low drag followed the Jaray design philosophy. While the long cars which had these curved rear body shapes probably managed to maintain flow attachment, the flow over the rear of the shorter cars became separated as the body curvature increased, and the drag was increased. Kamm proposed that by cutting off the body where

the flow separated would create a more practical shape. The same concept was first patented, however, in 1936 by Koenig-Fachsenfeld and is found in [6], (for the US version of the patent see [22]), who had worked with Kamm at Stuttgart University. While Koenig-Fachsenfeld emphasised the benefits to packaging and manoeuvrability, Kamm advocated the stability enhancement, especially in crosswinds, from the shorter blunter rear shape.

The so-called Kamm tail is popularly taken to mean a sharply cut off rear end shape on a car. However Kamm's designs, and he built four cars to demonstrate his principles, did not exhibit this feature. Cars K-2, K-3 and K-4 had blunt rear ends and all had well-rounded trailing edges, while K-1 had a rounded rear end and was described as 'blimp' like. The sharply cut off tail is, however, clearly described in Koenig-Fachsenfeld's patent.

The other misconception is that the cut-off tail achieves the same low drag as a fully streamlined tail. Neither Kamm nor Koenig-Fachsenfeld make this claim. What they could achieve was a better drag than a design with a longer, but curved, tail, especially if the flow separated before the trailing edge. As shown in this paper the available limited data on this subject shows that drag increases as a streamlined tail is truncated.

Conclusions

A common perception is that a tapered afterbody can give almost the same aerodynamic drag benefit as a streamlined tail.

A review of the published data investigating the drag benefits from a fully streamlined tail has been undertaken to understand the penalty which arises when the tail is truncated.

The potential drag reduction from a streamlined tail increases as the forebody drag is reduced and the effects of truncation are similarly increased.

The data suggests that the drag increase is approximately proportional to the increase in base area.

A CFD simulation of a tapered tail on the Windsor Body supports this linear relationship.

Because the data is sparse an alternative interpretation is that drag increases with (base area)^{1.5} as proposed by Hoerner for axisymmetric bodies.

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Definitions/Abbreviations

A	Frontal area
A _B	Base area
C _D	Drag coefficient = $2D/\rho U^2 A$
C _L	Lift coefficient
D	Aerodynamic drag
D'	Diameter of axisymmetric bodies
H	Body height
L	Aerodynamic lift
L'	Body length
L _R	Roof slope length
L _T	Tail length
Re	Reynolds Number
W	Body width