Laminar Flow Control, From Prandtl to Supercar X-Factor

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***Abstract*—For supercritical transport category aircraft flying at cruise, skin friction drag can represent more than 50% of the total drag on the aircraft. This is a result of the majority turbulent flow from the leading edge of the wing back. Laminar Flow Control is a technology by which you actively control the boundary layer with suction to delay the transition from laminar to turbulent flow in order to reduce the skin friction. While the principles of this tech have been studied on various aircraft, one auto company, Gordon Murray Design is hoping to use the principles of Laminar Flow Control to provide their new supercar a performance edge. In my paper, I'll examine the history and principles of Laminar Flow Control, detailing the hurtles traversed throughout its development before investigating the claims made by Gordon Murray Automotive's T.50 supercar and its unique aerodynamic configuration.**

***Index Terms*—laminar flow control, AA200, supercar**

I. INTRODUCTION

Laminar Flow Control (LFC) has long been a topic of interest in the aerospace industry. With laminar flow over a surface like an airfoil, it is often possible to achieve significant reductions drag compared to turbulent flow. In "A history of suction-type laminar-flow control with emphasis on flight research", Albert Braslow notes a potential efficiency gain of 30% is possible [7]. The predominant method for achieving this effect is via boundary layer suction in which suction is applied to the surface such that the boundary layer is removed and the flow remains attached to the surface further along the chord than it would have otherwise. While this topic had captured my interest in the past, the unveiling of a new supercar, the Gordon Murray Design T.50 reignited my interest in the topic. This landmark new supercar promises incredible performance on the road made possible in part by its unique aerodynamic design. A key aspect of this design is a fan. Via intelligent use of this rear mounted, in-body fan, the company claims improvements in drag at high speed and in downforce for help in cornering and braking. By interacting with both the upper and lower surfaces of the vehicle this fan pulls from many of the concepts of Laminar Flow Control (LFC).

To understand how and why this works on this car, we have to look back at aerodynamic research from the past century and a series of test aircraft which employed this technology. In looking back at the history of this technology, we can evaluate the claims being made by Gordon Murray Design and their T.50. This investigation will also shed light onto why this promising technology has found limited application in production aircraft and automobiles.

This paper will first look at the early developments in Laminar Flow Control, before looking at the series of test aircraft that used this technology. We will then look at the current state of art aircraft and research into LFC before transitioning into the automotive connections and finally looking at the Gordon Murray T.50 supercar, the claims the company makes, and the possible implications for the expanded use of this tech in other road vehicles. Finally, we'll wrap up with concluding thoughts on Laminar Flow Control technology.

II. LAMINAR FLOW CONTROL DEVELOPMENT

A. Early Years

As with many topics related to boundary layers and aerodynamics, Prandtl was one of the first to propose the idea of boundary layer suction [1]. Just a few years after coining the concept of a boundary layer in 1904, Prandtl proposed two methods for boundary-layer control [1]. Via suction, Prandtl and his colleagues outlined the possibility of delaying separation of the boundary layer particularly for airfoils at large incidence angles [1]. He also proposed "blowing" air over the leading edge of the wing to reenergize the boundary layer flow and prevent separation.

In early experimentation in 1935, Prandtl was able to work out empirically the minimum suction rate he believed was required to maintain laminar flow [1]. This equation (stated below as equation 1) was a groundbreaking development. Later, with more advanced modeling and simulation, we could further refine this lower bound and additionally provide an upper limit for the suction [6]. This will be detailed later in this paper. Hinted at in Prandtl's early work was the tradeoff between the power required to provide this suction and the actual drag benefits of such a suction system. Applying boundary layer suction over large areas would require significant power. This could be greater than the power reduction accompanied by a decrease in drag.

$$V_{w,minlaminar} = -2.18\sqrt{-v\frac{dU_e}{dx}} \tag{1}$$

To achieve LFC, we have established that we need to suck some of the air through the surface of the wing. This was not a trivial problem for early researchers. As we will see in many of the development aircraft, many early designs used small spanwise slots into the wing upper surface. As we know from class, separation will typically occur first on the upper surface of a lifting airfoil due to a less favorable pressure gradient compared to the lower surface. The relatively large size of these upper surface slots made them susceptible to debris intake and thus rendered their performance substantially reduced over time. Gregory noted in 1961 that slots lost effectiveness particularly with swept wings and that porous or perforated surfaces should be used instead [12]. It was soon determined that a porous skin on the wing, or a skin that had many small holes was the way forward. A much later example of what this might look like is found in Figure 1. This double layer skin separated the below surface area into distinct modules whose pressure could be individually controlled via valves. It would be decades after Prandtl before the manufacturing technology existed for this type of design to be feasible.

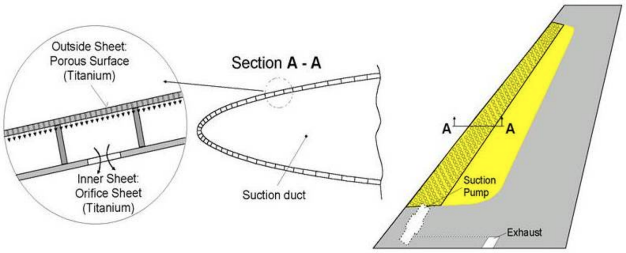

Fig. 1. Schematic of A320 ALTTA system with Porous Skin [17]

B. LFC and HLFC Distinction

Even after this brief introduction, it is aparent that achieving artificial laminar flow via LFC is complex. The obvious question to ask is, why not just design for natural laminar flow in the first place? In class and in literature it's made clear the challenges presented by natural laminar flow (NLF). Some of these include limitations on wing sweep, the requirement of favorable pressure gradients (which have impacts on wing shape and volume), and poor off cruise design performance with the potential for severe performance degradation if tripped into turbulent flow. Natural laminar flow is simply not feasible for the majority of large transport category aircraft. With LFC, it is possible to maintain laminar flow beyond chord Reynolds numbers typically seen as transitional or turbulent in the absence of LFC. This is not reestablishing laminar flow from an already turbulent flow. This would be a different objective, called relaminarization, and would require an order of magnitude more power [10]. Even with just LFC, a system requiring suction over the full or majoritity of the wing chord is extremely complex. As we will see later, its optimal operation requires different amounts of suction based on the span and chord location of that suction. Early on in LFC development and experimentation, researchers developed an alternative.

This alternative, Hybrid Laminar Flow Control or HLFC, only requires suction on the leading edge of the wing [13]. Figure 2 is useful for seeing the difference between no LFC, Natural Laminar Flow (NLF), LFC, and Hybrid LFC. HLFC is particularly useful for larger transport category aircraft whose cruise operation sees turbulent flow from near the leading edge all the way along the chord [13]. Using suction on the leading edge only is sufficient to delay this turbulent transition with much less power required. Combining this leading edge suction with less aggressive sweep angles and more favorable pressure gradients makes HLFC systems work with comparable drag reductions to LFC with significantly less complexity and power draw [10]. A plot of the percentage improvements in lift over drag from a NASA study can be found in Figure 12 in the appendix.

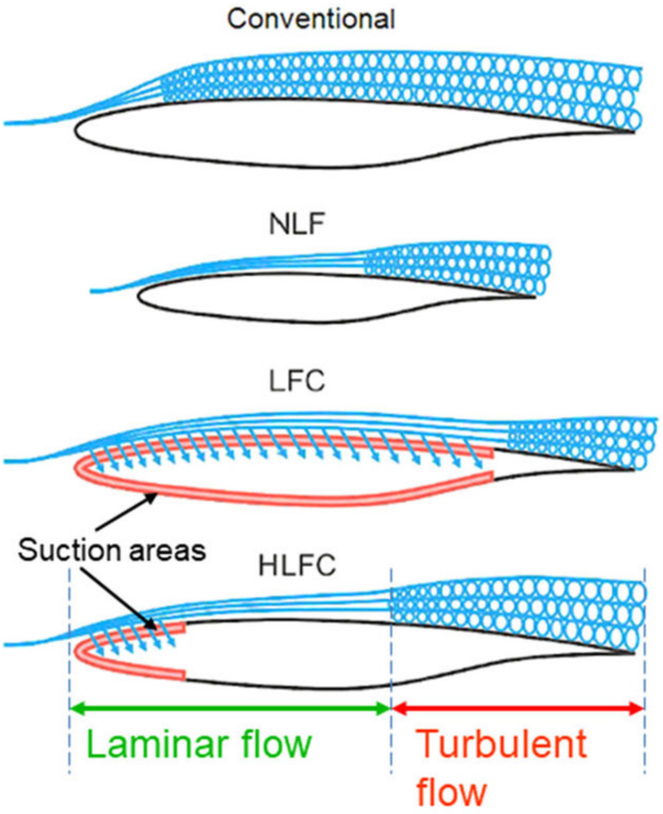

Fig. 2. LFC and HLFC comparison [13]

LFC and HLFC designs are intended to be used in cruise. It is seen as very difficult to design a suction system to work across all operation conditions from takeoff to cruise to landing and most systems have been optimized for level cruise flight. One of the reasons for this is the need to avoid debris ingestion at low altitudes. In [12], Ronald Joslin notes that the benefits of LFC will be greatest in long range aircraft which spend large percentages of their flight time in cruise.

C. Understanding Transition

Key to a successful LFC or HLFC design is understanding the boundary layer transition. In the development of boundary layer theory, Tollmein and Schlichting discovered convective traveling wave instabilities, T-S for short, which is a dominant factor in transition [10]. In addition to this, Cross Flow (CF) disturbances are crucial particularly for swept wing designs. From 0-25 degrees of sweep, T-S disturbances dominate the transition dynamics, from 25-30 degrees, there is a combination of the two, and above 30-35 degrees, CF disturbances dominate the transition dynamics and this often occurs very near the leading edge of the wing (the flow is entirely turbulent in this case) [10]. This lends credence to why HLFC is positioned at the front of the wing for large transport category aircraft as the transition to turbulence occurs almost instantly. For lower performance aircraft, LFC flow control can be found further back on the wing and still achieve the desired effect as the leading section of the wing chord is laminar before the pressure recovery occurs further along the wing. In general, reducing sweep is often required to maintain any natural laminar flow. For HLFC designs, it is often beneficial the reduce the sweep, but this incurs penalties for the maximum operating speed of the aircraft.

While transition has largely focused on wing geometry, the fuselage also plays a key role in transition. The root of the wing and its interaction with the fuselage can cause significant turbulence. Strong suction near the wing root is therefore necessary for some designs to make sure this turbulence does not spill onto the wing [3]. As we will see in some of the test aircraft, LFC systems are often mounted futher outboard on the wing, principally to isolate this effect for testing. More advanced modeling and CFD can help LFC system designers understand the suction requirements for a given wing location and is an area of active research.

III. KEY TEST AIRCRAFT

In this section, we'll look back at some of the key test aircraft used to validate results from LFC theory. Each aircraft lent key insights that have been used by subsequent aircraft and research to further the field.

A. Early Test Aircraft

An aircraft called the X-21A in 1963 was a modified aircraft where the bleed air from the engines drove a compressor that sucked the boundary layer through slots carved into one of the wings [7]. Although effective, the X-21 proved difficult to maintain. The wing contained an astonishing total of around 800,000 slots. Figure 3 shows a top view of this aircraft. Note the differences between the left and right wings and the surface finish. It's not hard to see that this now porous surface could get clogged with debris and bugs, which continued to plague LFC designs after the X-21A. It is noted in their test flights that the cooling of air over the wing intensified by the LFC system could cause icing to form on the wing surfaces. This would frequently trip the laminar flow back to turbulent flow abruptly. Flight through clouds could often introduce ice crystals onto the wings leading to significant degradation in the performance and laminar flow. Key insights were gained from the project however, namely the importance of surface irregularities and 3D span wise flow effects. This would go on to motivate further research into the area.

Fig. 3. Top view of X-21A Aircraft [7]

After a lull in interest in LFC, the 1970s saw a reemergence of the interest in the tech, primarily due the OPEC oil embargo and the fear of increasing fuel prices. The promises of increased fuel efficiency were too tantalizing to ignore.

The NASA Jetstar flight experiments of the 1980s were a significant contributor to LFC research [7]. It had leading edge test sections which were swept at 30 degrees, involved 20% of the span and 12% of the chord. It was designed to simulate supercritical pressure distributions from Mach 0.7 to Mach 0.8 and from 32k to 40k feet in altitude. The wings of the Jetstar had both slot and porous suction on both the upper and lower surfaces and had a liquid discharge system to prevent insect and ice accumulation. Different bug ingestion and icing prevention systems were tested in a long series of test flights with this aircraft. While less severe than the X-21, the effect of flight through clouds on disturbing the systems performance was also noted, although once out of clouds it was said that the performance quickly recovered. Significant progress was made in regard to bug ingestion and prevention with this aircraft throughout its life. A photo of one of the device fitted to the aircraft can be seen in Figure 13 in the appendix.

Another experimental aircraft, an F-16 modified to be an F-16XL-2 tested the possibility of using LFC in supersonic flight. This aircraft was built in the late 1980s and was prompted by interest in supersonic passenger aircraft [8]. They found that laminar flow was sustained for about 46% of the chord of the wing [8]. On this aircraft, a titanium glove surrounded the wing. Into the sleeve were more than 12-million laser drilled holes of nominal 0.0025 inches in diameter. The spacing between these holes varied depending

Fig. 4. F-16XL Test Aircraft [8]

on chord and span location. It went for about 17 feet along the leading edge and back about 60% of the chord. A photo of the aircraft and the skin can be seen below in the Figure 4. You can see that they extended the wing leading edge on the left hand side all the way until it met the fuselage. The advanced manufacturing techniques employed in this aircraft led to significant advances in performance of the LFC system. This was primarily due to electron beam perferated titanium. The drag reductions were not the only key takeaway from this test. The lower skin friction associated with laminar flow is even more important for supersonic flight as heating of the aircraft skin becomes a key concern. Aircraft like the Concorde and other supersonic aircraft had to keep the temperatures of the aircraft exterior in mind during their operation. An LFC system could potentially alleviate these concerns while also reducing drag.

The importance of the F-16XL tests was to show that LFC could facilitate laminar flow for both highly swept wings and wings that operate in the supersonic regime [8]. Additionally, it showed that the attachment line does not have to be at the leading edge of the wing for the flow to be laminar. Figure 5 shows the estimated laminar flow region from one of the supersonic test runs based on pressure data collected on the test panel. As you can see, large variations were found in the transition point which did not match exactly to the prediction techniques for transition they were using at the time [8].

B. Recent Aircraft

More recently, a Boeing 757 test aircraft from 1990 to 1991 was able to realize a drag reduction of 29% via a Hybrid Laminar Flow Control (HLFC) leading edge system [10]. As noted earlier, HLFC requires less system complexity and power. This more mature version of the tech showed the promise of HLFC on a transport category aircraft. In this testing, Boeing also showed the effect of using cooling to suppress T-S disturbances [3]. You will recall that T-S disturbances were the primary disturbance that led to transition in lower sweep angle wings.

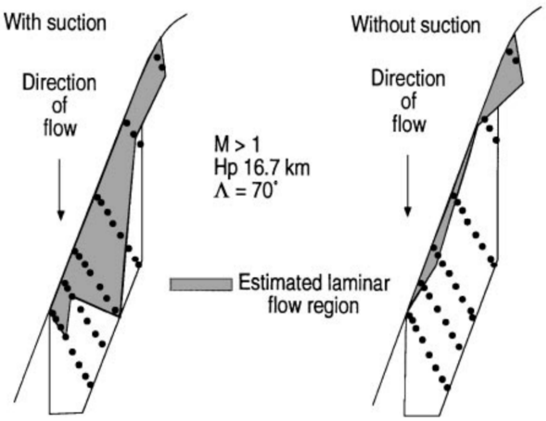

Fig. 5. Data from F-16XL Tests [8]

A recent case study in LFC not working as well as expected occurred with a small GA aircraft where they only found a 3.2% reduction in total drag [3]. This shed light that for smaller aircraft with less swept wings and for lower chord Reynolds numbers the skin friction drag reductions may not be as significant. This will motivate my later discussion on the T.50 supercar and the potential impact such a system may have in the automotive industry.

In recent years, Laminar Flow Control and Hybrid Laminar Flow Control have been experimented with by many different aircraft manufacturers and researchers alike. One example of this is experimentation done by Airbus with an A320. In 1998, the vertical stabilizer of an A320 was modified so that 20% of the stabilizer from the leading edge back had suction applied to it [17]. The reason why 20% was used was primarily due to the weight penalty currently found with this tech at the time. It was found to delay the transition to turbulent flow. As stated earlier, using only the front section of the airfoil with suction is referred to as HLFC [10]. Figure 6 shows a schematic of their test setup with the ducting required to facilitate the suction over the vertical stabilizer. In their testing they found that transition occurred around 36-38% of the chord without the system on [17]. With the system off they were able to correlate their models and better tune the suction amounts for when the system was turned on. Using infrared imaging and pressure probe data they were able to show where transition occurred [17]. Then with the suction turned on and calibrated, they found that separation occurred from 48-50% of the chord [17]. No data was available as to the drag reductions but this relatively simple system provided significant improvements in flow performance and showed the complete dampening of T-S and CF disturbances over the section of the stabilizer with the suction applied. It was noted that the transition aft of the suction occurred due to T-S disturbances [17].

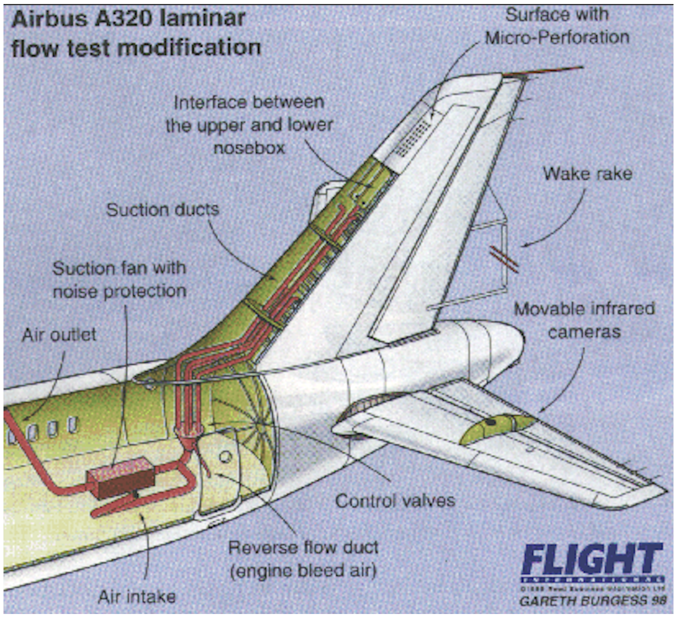

Fig. 6. A320 Laminar Flow Control Diagram [14]

An actual production application of HLFC is the Boeing 787 aircraft. This secretive application is found on both the horizontal and vertical stabilizers of early 787-9 aircraft and on the vertical stabilizer of the 787-10 series. While the exact details of how it works are a close trade secret, some sources give us a hint at how it functions. It is believed that microperforations on the front section of the control surfaces are fed via a dual hinged duct on the bottom surface of the horizontal stabilizer [9]. Depending on flight condition this flap can open to draw air in to provide suction to the surface or opened the other way to clear out the ducting form debris. The inlet and outlet door can be seen in Figure 7. It is suspected that no compressors or fans are used in this design, reducing its complexity and weight. Boeing officials note that it can be pressure washed and that no special attention is required to this section of the aircraft [9]. This marks the first commercial application of the technology and is a promising sign for the future of the tech in transport category aircraft. Hopefully we'll see this tech brought to the main wings of the aircraft in the near future. (One slightly unfortunate note is that Boeing, in an effort to streamline production, removed the tech from the horizontal stabilizer of the 787-9 to add commonality to the 787-10. It's unclear the performance merit of one or both systems, but it's an unfortunate step backwards in my opinion). Hopefully on the next series of aircraft from The Boeing Corporation will see HLFC added to more surfaces and with concrete claims as to their performance benefits.

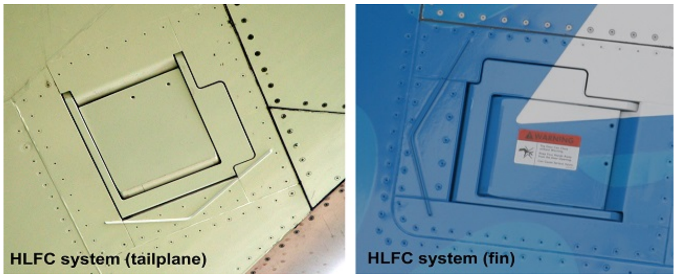

Fig. 7. Secretive HLFC Intake Doors for Boeing 787 [9]

IV. CURRENT DEVELOPMENTS

The consistent interest in the technology has elucidated many of the ongoing issues with LFC technology, some of which I've touched on already. In this section, we'll summarize these hurtles and point to some of the promising research being done to alleviate them.

A. *Key Challenges*

The main issue with many of the test aircraft was the design of the porous holes. In testing, they were easily plugged from a number of factors. One key factor was icing that occurred as a result of the lowered temperature across the now laminar section. Operating outside of a lab and in the real world exasperated these issues with small holes. Cloud formations with embedded moisture allowed ice crystals to form on the wings and in the holes. Not only did this plug the holes but it created surface irregularities which tripped the flow back to turbulent. With full LFC as was the case with several aircraft, simply turbulence in the air the aircraft was flying through was sufficient to trip the flow back to turbulent. This further emphasises the sensitivity of laminar flow.

Similarly, the issue of insect ingestion has been a known issue with LFC technologies. Insect prevention has been studied by Coleman in 1961 where he suggested mechanical scrapers, deflectors, covers that are removed after a certain altitude, continuous liquid discharge, among others. A Krueger flap was even used on a Boeing 757 in 1993 and in testing on the Jetstar by Collier and others [11] [7]. An often cited solution is to deactivate the system at low altitudes where debris and bugs are present before reactivating it when at altitude and free from these factors. Sealing or clearing these thousands or even millions of porous holes remains difficult.

B. *Active Research Areas*

Despite the application in the latest Boeing aircraft, LFC and HLFC is by no means a mature technology. According to [3], much additional research is still needed into the design, materials, and manufacturing of the porous skin. This involves designing such a skin to have long term durability, maintenance ability, low weight, and surface quality. Material science researchers have made huge advances in this regard and can now better predict the life cycle of these parts [10]. It remains to be seen what efficiency gains could be achieved by designing LFC or HFLC into the aircraft from the beginning, with suction being provided from the engines and airfoils designed specifically for the addition of the LFC tech on the surface [7]. This is particularly relevant for the anti-ice system required for commercial aircraft as this new surface presents many new challenges in this regard. As simulation techniques increase in speed and fidelity, it becomes more and more easy to design airfoils, fuselages and other surfaces with laminar flow control in mind. Several sail plane designs like that seen in [6] have taken advantage of this tech and used solar power to provide the relatively small amounts of power required to run the system.

Active suction systems must carefully be calibrated so that they provide the necessary amount of suction. More suction is not always a good thing as so much suction in an already laminar portion of the wing could result in increased skin friction and thus increased drag [3]. Research into the optimal suction and its distribution along with wing chord is critical. Finally, while extensive research has been conducted with wing surfaces with low sweep, supercritical wings like those found as the wings of transport category transonic aircraft experience significant contribution from spanwise flow. An optimal suction pattern for this may result in different hole spacing depending on the spanwise location [13].

As late as the late 90s, computation was not there to be able to investigate hole design. Namely, the inclination, geometry, spacing, and suction level and distribution [11]. This has been significantly advanced recently with new computation tools like those used in Boermans and Hemmens investigations [10] [6]. Here they used the e^N or N-factor method to calibrate their linear stability theory models to actual wind tunnel and real world data [17] [10]. Researchers at T.U. Delft have been leading the way in this modeling but I expect others are using similar transition prediction techniques [6]. The continued interest in this modeling will allow future systems to be effective, light weight and durable.

V. LFC Application to the Automotive Industry

As we move from the aviation industry to the automotive industry we see many parallels. Like aviation, drag is the enemy of many automotive designers. Reducing drag on a vehicle has direct benefits to fuel economy for internal combustion vehicles and range for electric vehicles. For a conventional vehicle, what benefits could we realize with boundary layer suction and laminar flow control? The obvious path here is to look at keeping the flow attached over the roof of the car. This would mimic the usage of LFC on airfoils. But first, we have to ask if this is even a major source of drag. The drag force on a vehicle can be found using this formula:

$$F_{drag} = \frac{1}{2}\rho v^2 C_D A_{frontal} \tag{2}$$

We see here that it is dependent on frontal area, velocity squared, and a coefficient of drag. This coefficient of drag can be reduced via the shape of the vehicle. A streamlined body, say something with a teardrop shape will have a lower Cd than a squared off SUV like a Hummer. Beyond reducing the frontal area, which is often limited by passenger volume and practicality, streamlining the body, and in particular, focusing on the rear end of the car will have the highest impact on the drag [4]. The wake behind a vehicle left as the upper and lower surface airflows separate from the vehicle before reuniting, creates a large low pressure area for non-streamlined body vehicles [2]. This low pressure area creates suction which has the effect of pulling the vehicle backwards, against the desired direction of travel. Figure 11 shows this blue low pressure region behind the vehicle. A streamlined body will reduce the volume of this region and thus have significantly less drag. Due to vehicle size limitations streamlining is not often possible. A good tradeoff is to shape the rear of the vehicle via a Kammback type design. This can be seen in Figure 8. Reducing the rear area to about 50% of the maximum cross sectional area of the vehicle before cutting it off has a good tradeoff between drag reduction and vehicle volume [4]. The effect of reducing the rear low pressure area, sometimes called the bay suction, has a larger effect on drag than the skin friction associated with the predominantly turbulent flow over a high speed vehicle.

Fig. 8. Honda Insight with Kammback rear design [15]

Another key consideration for performance vehicles is downforce. Downforce is the negative of lift and is used to push that car into the road for added stability while cornering or driving at high speed. The obvious way to achieve this is to attach a rear wing. This would be an airfoil flipped upside down to provide downforce as the vehicle speeds up. This can be carefully designed to have a good L/D, but significantly modifies the external appearance of a car. Underbody design, namely an object called a “diffuser” can be used to accomplish much of the same effect with a lesser visual impact. Mounted at the rear underside of the car, a diffuser is a gradual expansion of the flow underneath the car which serves to reduce the pressure ahead of the diffuser by speeding up the air and lowering its pressure [2]. While the 3D effects of vortices play a large role in the effectiveness of diffusers, the key principle is to expand the flow. This has the effect of sucking the vehicle to the ground. Complicated diffuser designs originating from Formula 1 race cars have led the way in optimal efficiency and high downforce, but the main takeaway is that without active control, there is a limit to how aggressively you can angle the diffuser up at the back in order to keep the under body flow attached to the diffuser [2].

VI. EVALUATION OF T.50 CLAIMS

Gordon Murray Designs (GMD) is a small British design group run by notable racecar and road car designer Gordon Murray. Their recently unveiled multi-million dollar T.50 supercar promises incredible performance made possible by a powerful V12 engine, lightweight design, central driving position, and innovative aerodynamic design. This aerodynamic design is centered around a rear mounted fan. This 8 KW fan has ducting which, depending on mode, can pull air from the upper or lower surfaces of the T.50 [5].

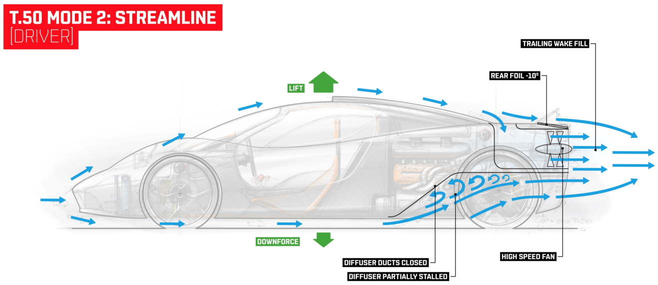

Fig. 9. T.50 Streamline Mode [5]

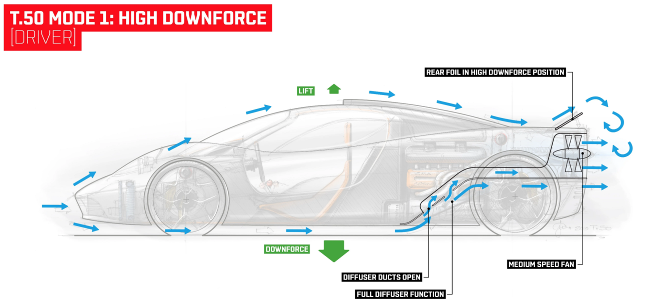

Fig. 10. T.50 High Downforce Mode [5]

The stated purpose of this fan is four fold. It is to aid in 1) cooling, 2) enhance downforce, 3) reduce drag, and 4) increase efficiency [5]. The second and third claim, to enhance downforce and reduce drag are of interest to this brief analysis.

In press material for the car, the designer claims the fan is used to keep the flow attached to the underside of the car as it traverses the diffuser. In this high downforce mode GMD claims the fan will increase in the efficiency of the diffuser by 30% for an overall increase in downforce of 50%. While not immediately apparent at what speed these claims are made, it appears to be at around 150mph via information contained in videos by the company [5]. In high downforce mode, the fan is used to suck the turbulent boundary layer to allow the flow to reattach to the diffuser surface further forward than it otherwise would. This is accomplished via a slot which the company says pulls air off the diffuser at a 90 degree angle [5]. Figure 10 shows this operation of the fan. From press material, it is not clear the dimensions of this slot, but we would assume that the dimensions are quite large compared to the micro perforations on some of the LFC designs we've discussed earlier as this area under the car could very easily be plugged with road debris. The positioning of this duct is something we can see from the press materials. It appears to be midway along the expanding section of the diffuser. On the pressure plots with the fan turned off, we can see that the flow separates immediately upon entering the diffuser as evidenced by the very lower pressure area shown. When switching on the fan, this low pressure area reduces in size, but is not eliminated. It's clear a tradeoff was made for the power output of the fan, and the overall aero balance of the car. We see that the suction here is not sufficient to reestablish anything resembling laminar flow from the already turbulent flow, but has the effect of making the reattachment occur further forward on the diffuser. The 11 blade, 400mm diameter fan is said to require 8KW to run at its 7000rpm max speed. This is about 10 Horsepower (HP). For a car that has 663 claimed HP, this represents about a 1.5% power draw for its usage. In the corners, this could be a wise trade-off.

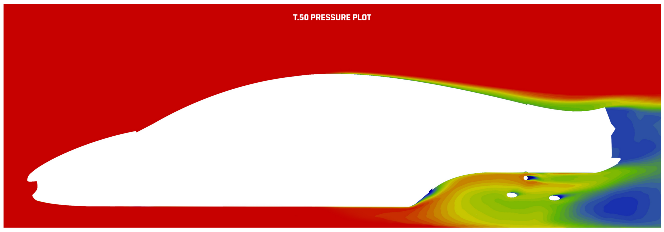

Fig. 11. T.50 Simplified Pressure Plot [5]

In streamline mode, Gordon Murray claims that drag can be reduced by 12.5% with the combination of stalling the diffuser (shutting off the suction ducts), reducing the angle of the rear airfoil spoilers, and sucking in the air from the top of the car via the fan [5]. Despite reaching out GMD, I was not able to ascertain any additional CFD data about the T.50 beyond what is published in press materials. While we do not have the full picture from CFD, it is hard to imagine that a streamlined vehicle like the T.50 will exhibit significant flow separation over the upper surface of the vehicle even at high speeds. So, the added suction from a very large intake to the fan on the upper surface will likely not contribute much to the overall drag reduction as the flow is turbulent, but attached.

For a passenger sedan with a steeply raked rear windshield followed by a pronounced flat trunk, we suspect that boundary layer suction could serve to reattach the flow earlier on, but the complexity and cost of such a system would be much more difficult than just streamlining the rear design of the vehicle.

We then look at the effect of filling the low pressure wake with air from the fan in this low drag, streamline mode. In this case we are pumping this low pressure area with air from the fan in an attempt to increase the pressure of this region. Doing so will effectively create a longer vehicle allowing a more gradual mixing of the upper and lower surface airflows. Figure 9 shows the fan operating in this mode. This is likely the most positive impact of the fan in this configuration, but without hard data from the company, it is difficult to verify. Other means of passively filling this rear vacuum with higher pressure air has been studied by other automakers and will largely fill the same roll as an active fan [4]. I suspect a large majority of the 12.5% reduction in drag is mostly created by the reducing in angle of attack of the rear moveable spoilers which instead of kicking up the flow to provide downforce, allow the flow to more closely follow the profile of the car and lessen the volume of the low pressure area behind the vehicle. This effectively makes the side profile of the car more similar to a teardrop shape which will reduce the Cd.

From this brief look at how the fan is used on the Gordon Murray Design T.50 we estimate that of its main uses, likely only two have any noticeable effect on the aerodynamics. These are the boundary layer suction of the rear diffuser and the pumping of higher pressure air into the rear wake of the vehicle. Without more data it is difficult to assess if the trade-off of added complexity and weight offset the styling penalty of a simple rear wing design. For a more conventional vehicle operating at highway speeds and below, a much simpler approach to reducing drag would be to streamline the aerodynamics, particularly around the rear of the car. Adding a fan to draw power from the motor or battery would likely have very little impact. However, for a performance cars operating at the threshold of tire grip, the added downforce may be worth it. When cornering you are not asking for 100% of the vehicle's engine output to accelerate you forward and the 1.5% power draw to add 30% more effectiveness to the diffuser could be a wise exchange. We hope that GMD will release more detailed specification about the fan aerodynamics in the future for car enthusiasts and aerodynamicists alike to study.

VII. CONCLUSIONS

In this paper, we looked at the development of Laminar Flow Control technology through test aircraft and research. These principles, mainly the positioning and size tradeoffs of these LFC systems helped us examine how a similar system could find its way into the automotive world with its different, but related objective to reduce drag and increase either lift or downforce. Finally, we looked at how the Gordon Murray Design T.50 uses boundary layer control and active aerodynamics to enhance its road performance.

Laminar Flow Control and Hybrid Laminar Flow Control promise large reductions in aircraft drag, on the order of 20-40%. This is huge and as we reach the limits of propulsion efficiency with high bypass gas turbines, this efficiency boost will be ever more critical in ensuring cleaner skies. In the future, I expect more aircraft to integrate boundary layer control technologies into tail surfaces, fuselage elements, engine nacelles, and finally onto the primary wings. When long term durability and redundancy is guaranteed and environmental interactions with bugs and icing are dealt with, this technology will revolutionize the aviation industry.

ACKNOWLEDGMENT

Thank you to Professor Kroo and the TAs for a great quarter. I will take with me many important insights into applied aerodynamics. I hope this paper was enjoyable and enlightening to read.

VIII. APPENDIX

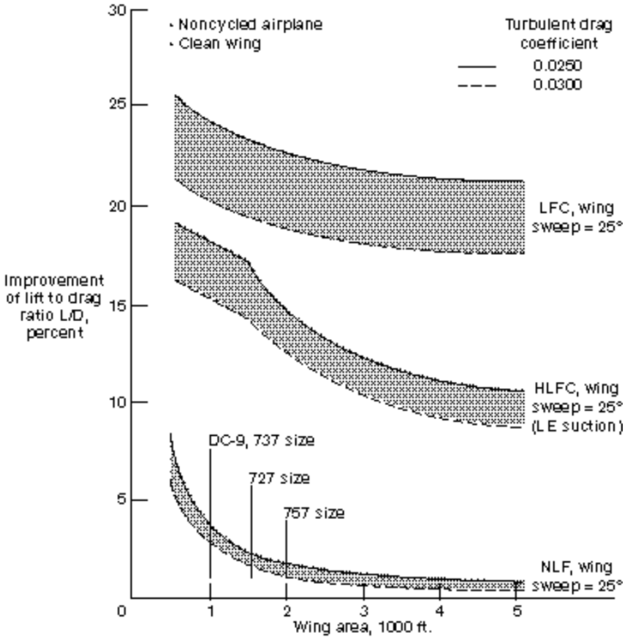

Fig. 12. Drag reduction for various low situations [7]

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Fig. 13. JetStar Test Aircraft [16]

Fig. 14. T.50 Rear Design [5]

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