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DREAMLINER III - SUMMARY OF WIND TUNNEL TESTS AND THE FIRST PHASE OF TEST DRIVING OF A LAND SPEED RECORD VEHICLE

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Abstract

In 1996 the Swedish car Dreamliner III established a new international land speed record over the flying kilometer for automobiles using 350-500 cc engines. In doing so it marked the end of the first phase of test driving of the vehicle and a wind tunnel test at the Volvo PVT full scale automotive wind tunnel followed. This paper outlines the design target and history of the project before discussing the results of the tests on the road and in the wind tunnel. The low aerodynamic drag of the Dreamliner III of C_D=0.168 and C_D*S=0.063 m^2 resulted in a strong performance potential of which only a small part has been possible to exploit due to poor handling qualities. The wind tunnel results indicated a slight tendency for front wheel lift, well within tolerable levels. The possibility of tailoring the drag, lift and yawing stability using various add-ons and quick fixes was demonstrated. Using a roll of tape, the drag can be reduced by up to 9% in only a few minutes, while still allowing short duration record runs.

Nomenclature

S = Reference area, vehicle frontal area
C_D = Vehicle drag coefficient
C_L = Vehicle lift coefficient
C_m = Vehicle pitching moment coefficient
C_n = Vehicle yawing moment coefficient
D = Vehicle drag force
L = Vehicle lifting force
β = Angle of sideslip
Δ = Aerodynamic coefficient in relation to the baseline configuration

Introduction

Would it be possible to design a vehicle being efficient enough to set speed records using affordable engines? Could it be built by two enthusiasts using only their spare time? Was eight months enough to go from preliminary design to an international land speed record?

In early 1996 we figured the only way to find out was to give it a try. The Dreamliner project was launched. With a common background in experimental aerodynamics combined with fields specialization like aircraft structures, fiber composites and the aerodynamics of low drag, high speed ground vehicles, we figured we had a pretty good start. Yet, had we known the amount of hours we were to spend in such a short time, we may not have gone ahead without getting paid for it.

Design target

The target for the Dreamliner is the kilometer speed records in the smaller engine displacement classes. The governing body for international automotive records is the Fédération Internationale de l'Automobile (FIA). According to the rules set forth by the FIA an automobile is defined as having at least four wheels out of which at least two are driving and at least two are steering. The wheels must not be on a single line. To set a speed record over one kilometer with a flying start, the automobile must pass the measured kilometer in each direction within an hour and the average speed is the official speed.

Project history

The project started in January 1996 with an invitation to a semi annual record attempt. Following a hectic spring, the chassis with most systems in function was driven at the Tullinge airfield near Stockholm, Sweden on May 26. On September 9 the Dreamliner was driven at an official speed record attempt in Falkenberg. Although still very much under development and far from its full potential, the speeds measured rendered the team an international record in the 350-500 cc engine displacement class.

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Concept

In designing a car for high speeds using small engines, a strict order of priority of design considerations was established. Driver safety was placed on top of the list with handling and ergonomy on second while performance related issues were found further down the list. Common sense was applied through the motto "don't let your hobby kill you".

Configuration

With the FIA rules and the safety aspects as a base, the whole vehicle was designed for the lowest aerodynamic drag being practically possible. Drawing from the team's previous experience in aerodynamic design of low drag automobiles, the configuration seen in figure 1 was chosen. The driver was placed in a supine position and a crash cage was designed around him. The front wheel assembly was placed in front of the cage. To the rear of the crash cage, an aft section was bolted. In the aft section the engines, drive train and rear axle were placed, one behind the other. Behind the rear wheels, the sides of the body were tapered down into a small base area providing for the braking parachute and engine zone ventilation. Thus the overall width of the car was determined by the width of the driver's shoulders. Overall vehicle dimensions are found in table 1.

In order to enable the car to run in different engine displacement classes, a universal engine mount was designed to facilitate easy engine changes. To indicate what engine displacement is used, the Dreamliner is designated a number corresponding to the FIA displacement class. Consequently, the Dreamliner III was driven in class 3, 350-500 cc.

Driving

The first phase of test driving was conducted during the summer of 1996, culminating with the setting of a new international record as mentioned previously. The Dreamliner III was initially tested without the body to verify all mechanical and electronic systems. Later test runs were performed with the complete body and all systems complete.

Ergonomy

Apart form the initial absence of adjustable pedals to accommodate the two different drivers, the driver's compartment has proven to be quite functional and reasonably comfortable. The driver's seat is in fact the only place in the workshop where any of the authors has fallen asleep during late night building sessions.

Due to its very small size, the Dreamliner is by no means practical and the driver needs assistance getting strapped down. Still emergency exits have proven to be fast. When the car is stationary, the heat build up in the driver's compartment is rapid if the canopy is closed. However, as soon as the car is rolling the ventilation effectively reduces the temperature to comfortable levels.

The field of vision for the driver was a main concern early in the design process. While driving, both drivers have found the vision to be quite satisfactory. However, when the car is stationary it has proved necessary to keep the canopy open as the driver is otherwise unable to establish eye contact with the crew due to the limited upward visibility.

Handling

This has proven to be the Achilles heel of the Dreamliner during the first phase of testing. The primary problem became evident during the very first test run. The desirable amount of front wheel movement for a given steering wheel input had been greatly overestimated. The car was very sensitive to steering inputs even when all adjustments possible were made to reduce the sensitivity. It was decided to proceed with the first test phase with the sensitive steering and letting the drivers judge how far the speed envelope of the car could safely be opened.

During one of the later test runs the car did exhibit serious over steering in a very erratic way. Subsequent analyzes showed that a series of factors were aggravating an overseen roll-yaw coupling which in turn caused the car to oversteer violently. Among the contributing factors were excessive tire pressure, unfortunate front wheel angles and mechanical play in the spherical bearings of the rod ends used. When the wheel angles, tire pressure and steering mechanism had been adjusted, the car displayed excellent tracking and only the over sensitive steering remained a limiting factor on performance.

Performance

From the first test runs it was evident that the drag was low and that the somewhat heavy construction still would provide adequate acceleration. With all body panels in place the drivers has estimated that at 170 km/h only about 40% of the available power, or about 20 bhp is used. Most of the somewhat unorthodox systems in the car have proven to work beyond expectations.

At the end of the first test phase the maximum speed of the Dreamliner III had been measured at about 180 km/h. Due to the sensitive steering, no more than high idle on fourth gear has been used, leaving the fifth and sixth gear to be explored during the next test phase.

Wind tunnel testing

In late 1997 the Dreamliner team was invited to the Volvo full-scale automotive wind tunnel PVT in Gothenburg. One shift of twelve hours was made available for installation, testing and returning the facility to its initial condition.

Experimental equipment

The PVT wind tunnel is a low speed wind tunnel designed for automotive testing. The test section measures 6.6 by 4.1 meters, the ceiling and walls are slotted to reduce the sensitivity to model blockage. To reduce the boundary layer on the floor, suction is applied on the test section floor, about 2 meters upstream of the turntable. An external balance is used for force and moment measurements. In normal operation, the wheels of the vehicle are placed on pads attached to the balance. The pads are flush with the test section floor. The narrow track of the Dreamliner necessitated extensions of the pads toward the centerline of the wind tunnel. These extensions increased the ground clearance of the vehicle by about 10 mm, a figure close to the nominal displacement thickness of the boundary layer at the center of the turntable. The drag of the isolated balance pad extensions was measured and a small correction has been applied to the measured vehicle drag data. No corrections were made to the lift data although the extensions did allow some air to flow between the wheels and the test section floor.

An initial Reynolds number variation performed at $\beta=0^\circ$ indicated that the baseline configuration was rather insensitive to Reynolds number. The bulk of the testing was performed at a medium wind speed of 27.8 m/s.

For reasons not clear by the time of writing, there was an offset in the side force and yawing moment measurements which does not seem to be coupled to the geometry of the vehicle. This offset is treated as an error in the measured data and not discussed further in this report.

In order to assess any hysteresis, some runs were performed as β-sweeps from -15° to $+15^\circ$ as well as from $+15^\circ$ to -15°. Figures 2, 4 and 5 show data taken while sweeping in both directions.

Flow visualization

Using smoke and tufts, the flow around the vehicle was surveyed at different airspeeds. The flow was found to remain remarkably well attached even at angles of sideslip up to 20 degrees. The only separated regions found were behind the exposed part of the wheels and the open base area of the body. The wakes from the wheels did interact with flow on the sides of the car by causing a light "wiggling" of tufts in some areas, but no reversed flow could be seen using any method of visualization.

Drag

In the baseline configuration, the Dreamliner did exhibit a quite low drag coefficient of $C_D=0.168$, or an equivalent drag area (C_D*S) of 0.063 m^2 at $\beta=0^\circ$. An interesting comparison is that this drag area is very close to the drag area of the rear view mirrors alone on a regular car. Some asymmetry can be seen over β due to geometry imperfections in the body of the vehicle while no significant hysteresis is apparent (figure 2). Even the strongest crosswinds considered for safe operation of the Dreamliner should not increase the drag more than a few percent, which is important when the opportunities to set records are limited.

A drag decomposition test was performed and the results are shown in table 2. It can be seen that the internal drag of the engine compartment overshadows the benefit of dumping the ventilation air into the wake behind the car. However, this balance is likely to change when the air flowing through the engine compartment is heated by the running engine. Sealing the engine compartment ventilation and fairing the aft end of the body results in a ΔC_D of -0.016, or almost 10% of the drag of the baseline configuration. The effect of sealing the driver's compartment ventilation is $\Delta C_D = -0.006$, or slightly less than 4% of the total drag. Taping all body panel junctions resulted in a ΔC_D of -0.002 or about 1.3%. However, this included the canopy, something unacceptable for safety reasons. If the canopy is left untaped, the drag is reduced by a ΔC_D of -0.001, less than one percent of the total baseline drag.

Although the braking parachute is only 0.6 m in diameter it increases the drag coefficient of the vehicle to $C_D = 0.90$, or an increase of more than 400%.

The addition of a front spoiler, or dam, reduced the drag by almost one and a half percent. Even if this reduction may be linked to the increased ground clearance during the test and the wind tunnel floor boundary layer, the use of a spoiler to tailor lift distribution can apparently be done without any significant adverse effects on drag.

The addition of a vertical fin did increase the drag at zero sideslip slightly, while the leading edge suction of the fin tended to reduce drag at $\beta=10^\circ$ and higher (figure 3).

Lift and pitching moment

Since the Dreamliner was designed for straight line, dry concrete or asphalt tracks only, there was no need for negative lift, or "down force". As expected, the car did show a slight lift, increasing with angle of sideslip (figure 4). The pitching moment was slightly positive at small angles of sideslip as seen in figure 5. At $\beta=0^o$, $C_L=0.172$ and $C_m=0.0078$ was measured. Looking only at the coefficients of lift and pitching moment, the magnitudes may seem alarming, but the forces are not all that large. At the design top speed of 70 m/s the lifting force at the front and rear wheels are 106 N and 88 N respectively. Compared to the total mass of the vehicle being around 3500 N, the aerodynamic lift and pitching moment are unlikely to cause any problems. Should this assumption prove false, the above mentioned front spoiler can reduce the total lift by $\Delta C_L=-0.049$, or almost 30% and the pitching moment by $\Delta C_m=-0.028$ at $\beta=0^o$. This is equivalent to reducing the lift at the front wheels to half the value of the baseline vehicle.

Lateral stability

The issue of lateral stability evolves into two quite different problems depending on the capability of the tires to generate side force. The most simple case is when the wheels do not generate any side force, as in the case of water planing. Lateral stability is reduced to the positions of the center of gravity and the center of pressure. However, if the wheels are generating side force, the geometry of the front suspension comes into play and the behavior of the vehicle becomes more intricate to analyze. A vehicle which is not aerodynamically stable in the case of water planing is not desirable, neither is one which weathercocks into a crosswind due to aerodynamic over-stability. To provide input to future analyses of lateral stability, the Dreamliner was tested with a fin, which was cut down in size during subsequent runs. A point half way between the wheels has been used as a moment reference point since this is expected to fall close to the center of gravity with coming engine alternatives. In figure 6 the influence on yawing moment by fin area can be seen. The fin is clearly efficient in producing a yawing moment all the way up to $\beta=15^o$.

Effect of ground clearance

One run was performed at $\beta=0^o$ with the ground clearance increased by 10 mm. The increase was performed by adding 10 mm thick spacers between the wheels and the balance pad extensions. As the spacers themselves were included in the balance measurements, the accuracy of the drag measurement at high ground clearance is questionable.

Increasing the ground clearance resulted in a $\Delta C_L=-0.017$ or a reduction of 9.9% while the pitching moment showed a $\Delta C_m=-0.006$, indicating that most of the change in lift occurred at the front of the car. The drag increased by a $\Delta C_D=0.009$ or 5.3%. The increase in drag with increase in ground clearance contradicts previous results for bluff bodies in ground proximity reported by Hucho[1] and Hoerner[2] but may be explained by the above described spacers.

Effect of angle of attack

The angle of attack was changed by using the same spacers as for changing the ground clearance. The spacers were in this case placed either under the front wheels of under the rear wheels. Due to the nature of this procedure, the overall ground clearance of the vehicle was increased as the angle of attack was changed from neutral. As in the ground clearance test, the spacers were included in the balance measurements, affecting the drag measurement.

Lifting the front wheels to achieve 0.17° angle of attack, the drag increased by $\Delta C_D=0.006$, or 3.6%, with no significant changes in lift or pitching moment. Lifting the rear wheels by the same amount produced a ΔC_D of 0.002 (1.2%) while C_L was reduced by 0.019, or 11%, and pitching moment is cut in half by a $\Delta C_m=-0.004$. Attempting to separate the influence of ground clearance from the influence of angle of attack was not considered meaningful due to the small material available. From an engineering point of view it seems like if reasonable changes in angle of attack due to track irregularities or tire pressure will not pose a problem to safety or performance.

Concluding remarks

The Dreamliner project has proven the possibility of designing, building and operating a land speed record vehicle with extreme aerodynamic efficiency within a short time frame and a minimal budget. Although presently the holder of one international record, the testing of the Dreamliner will continue in order to take the last flaws out of the design and proceed toward future attempts on other records.

Performance

No immediate improvements on the efficiency of the car are planned. When changing engines for different classes, an increase in power available is expected as the current power plant is rather conservative.

Handling

A reduction gear for the steering is under construction, which will hopefully solve the problem of steering sensitivity. More test runs will be performed during crosswind conditions to determine the need for a vertical fin.

Acknowledgments

The authors wishes to thank Volvo for their invaluable support in providing access to their wind tunnel facility.

References

[1] Hucho, W-F, "Aerodynamics of Road Vehicles", Butterworths & Co., 1987

[2] Hoerner, S. F., "Fluid-dynamic drag", Hoerner Fluid Dynamics, New Jersey, 1965

Length	5.36 m
Height	0.74 m
Width	0.57 m
Weight including driver	350 kg

Table 1. General dimensions.

Geometry change	ΔC_D
Sealing the engine compartment ventilation	-0.008
Sealing the engine compartment ventilation and fairing the base area	-0.016
Sealing the driver's compartment ventilation	-0.006
Taping all body panels	-0.002
Taping all body panels except the canopy	-0.001
Front spoiler (dam)	-0.002
Braking parachute	+0.732

Table 2. The influence on drag of different geometry changes.

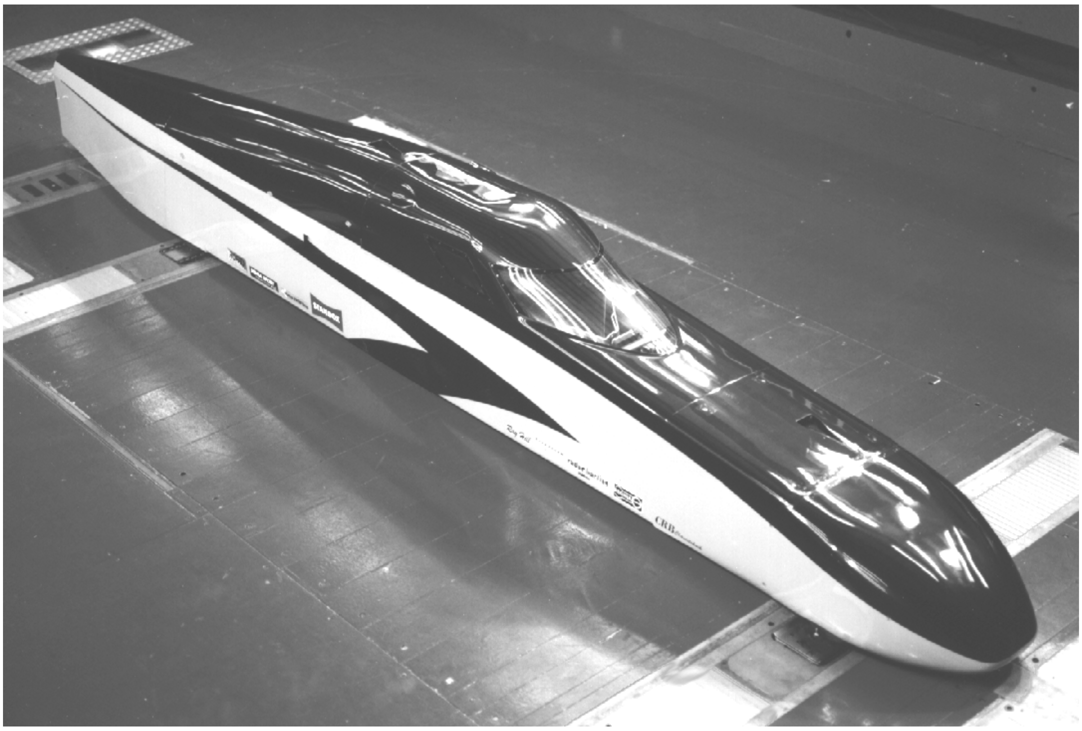

Figure 1. The Dreamliner III in the Volvo PVT wind tunnel.

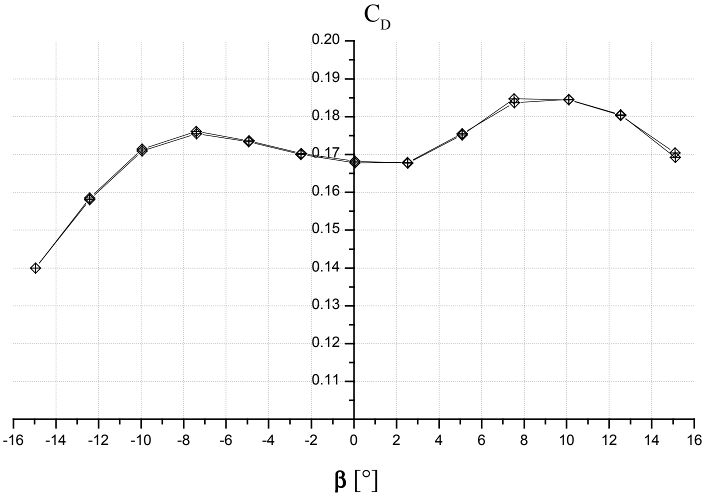

Figure 2. Drag for baseline configuration.

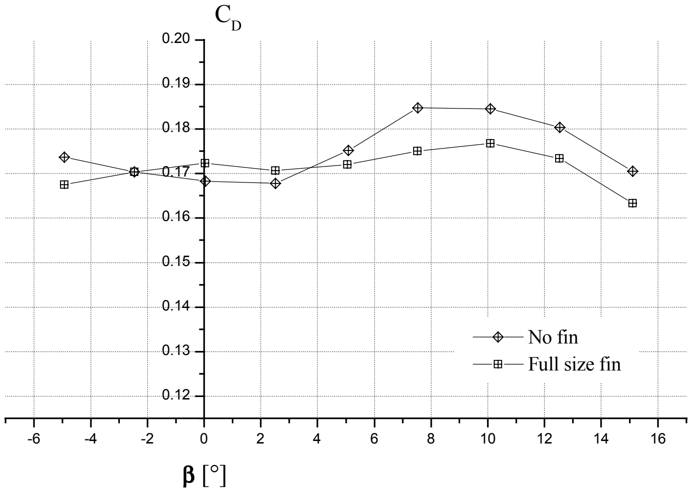

Figure 3. Drag for baseline configuration with and without fin.

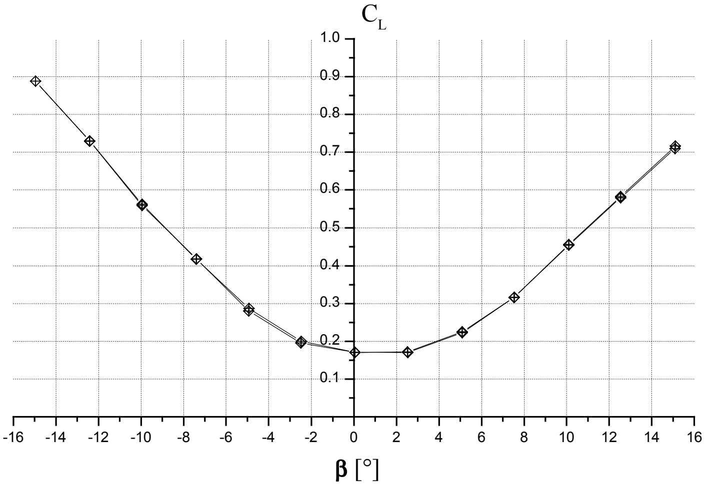

Figure 4. Lift for baseline configuration.

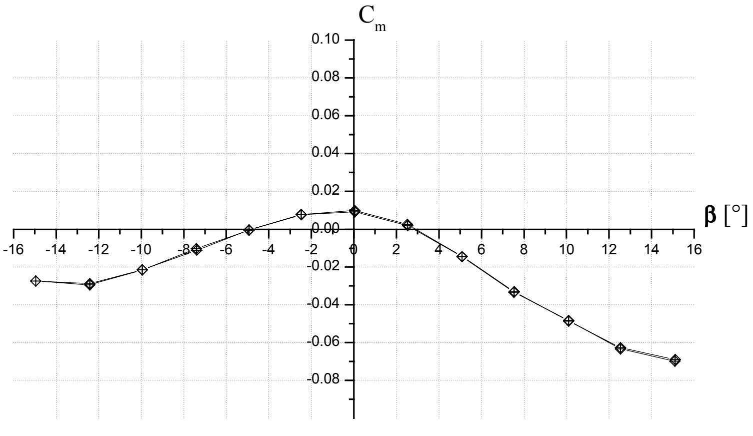

Figure 5. Pitching moment for baseline configuration.

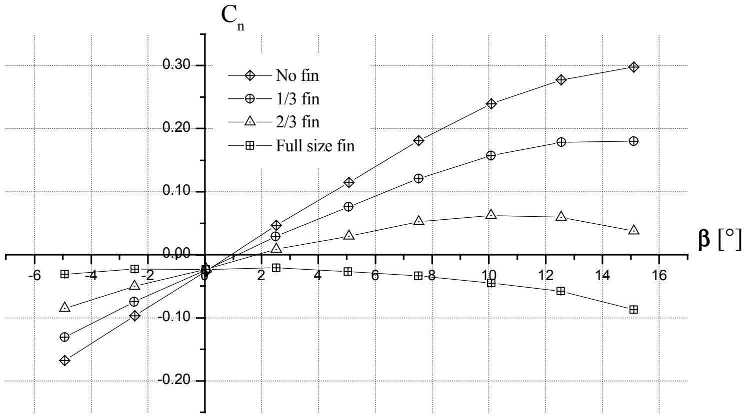

Figure 6. Yawing moment for different fin sizes.