CONCEPTUAL DESIGN STUDY ON LH_2 FUELED SST - ENVIRONMENTAL IMPACTS REDUCED BY AIRFRAME/PROPULSION SYSTEM INTEGRATION -

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Abstract

Next generation supersonic transports (SST) should have not only better aircraft performances but also less environmental impacts including sonic boom, emissions, and engine noise. With an increasing concern over the environmental and energy problems, alternative fuels have risen in significance. In this context, the authors have conducted a conceptual design study on LH_2-fueled SST.

In order to obtain a solution which has better aircraft performances and less environmental impacts, airframe and propulsion system integration is needed. By using our conceptual design environment, a global analysis on LH_2-fueled SSTs has been conducted in comparison to kerosene SSTs.

The result of the global analysis has shown that the optimum cruise altitude of LH_2 SSTs is higher than kerosene SSTs. In addition, one of the active constraints which determine the feasible design space is climb capability at cruise altitude. Then, suggestions have been made for improving the feasibility.

1 Introduction

NASA announced stringent goals concerning what future SST systems should accomplish, including cruise efficiency, sonic boom, airport noise and NOx emission as shown in Fig 1.1.[1] In addition, it was reported by the IPCC that water vapor emissions in the stratosphere, where SSTs tend to fly, could have a significant impact on global warming.[2]

With an increasing concern over the environmental impacts and energy problems, alternative fuels have risen in significance. Hydrogen-fueled aircraft were studied by NASA in the 1970s [3] and by EU in the 2000s [4]. The study conducted by NASA in the 1970s concluded that the LH_2-fueled SSTs provided advantages in nearly every category including cost, sonic boom, airport noise, and emissions. One of the remarkable results is the 50% reduction in takeoff weight by the higher energy density. It should be noted that the 1970s were still a transition period of low sonic boom technology and climate change research work.

Considering this background, the authors have conducted a conceptual design study on LH_2-fueled SST. Our study started with the feasibility study which focused solely on airframe system.[5-6] After that, in order to evaluate the overall feasibility, the evaluation of propulsion system was added in our conceptual design environment.[7] Using the design environment, the aircraft performances and environmental impacts of LH_2-fueled SSTs were assessed in comparison to kerosene fuel.[8] This paper will discuss the feasibility of LH_2 SSTs which is evaluated by considering aircraft performances and environmental impacts from the perspective of both airframe and propulsion system by conducting global analysis.

2 Conceptual Design Environment

In general, conceptual design, which is performed in the upstream phase of aircraft design, often suffers from little available information. In order to fill the lack of information, the physics-based models are used in the aerodynamic and engine performance evaluation module, which are packaged in the conceptual design environment as shown in Fig. 2.1.

A 3D panel code PANAIR [9] is utilized for the evaluation of aerodynamic performances including lift, pressure drag, moment, and near field signature. Viscous drag is obtained by a free source code FRICT [10]. These codes are selected for the speed and accuracy of conceptual design. A commercial code GasTurb [11] is used for the evaluation of engine performances including thrust, specific fuel consumption, jet velocity, and engine parameters (p3, T3, and T4).

Among several aircraft performances in this study, the estimation of weight performance is the most difficult but critical performance. A conventional statistical approach is selected in this study.[12] The regression models of each weight components are constructed using the historical data of previous SST concepts.[13-16] After that, the regression models are modified using the weight data of Concorde.[17] Some additional components, such as tanks, have to be considered in the estimation of the weight of LH_2 SSTs, which will be explained in Section 4.1.1.

One of our main interests is to see how the requirements for environmental impacts affect the specifications of SSTs. The evaluation items in this study are sonic boom, airport noise, NOx emission, and water vapor emission (climate change impacts). The evaluation methods here have to be simple enough to be applicable in the conceptual design phase.

In the sonic boom estimation, two methods are prepared. One is the first cut method by Carlson which outputs the pressure rise of sonic boom under the assumption of N-wave.[18] The other is a more accurate method which can consider the 3D shape of aircraft. The near-field signature is calculated using PANAIR while the far-field signature is obtained using the Thomas's method.[19-20] After that, the far-field signature is evaluated in PLdB.

For the airport noise, only sideline noise is evaluated in this study using the following equation (1) which is derived from Ref.[21]. In general, the jet velocity is a determinant of the sideline noise of SSTs among the possible causes.

$$EPNL = 95 + (100 - 95)\frac{(Vj - 1450)}{(1750 - 1450)} \quad (1)$$

For the NOx emission, the following simplified equation (2) is utilized.[22] This equation requires the engine parameters of p3, T3, and T4. That is why GasTurb is utilized.

$$EINOx = 4.19 \times 10^{-3} T_4 (\frac{P_3}{439})^{0.37} e^{(T_3 - 1471)/345} \quad (2)$$

Water vapor mitigation was stated in the N+3 goals. This is because water vapor emissions in the stratosphere could have a significant impact on global warming according to the IPCC report. In addition, it is predicted that the emission altitude will also affect global warming because as emission altitude increases, the residence time of water vapor will extend. As IPCC cautioned, it is necessary to consider the global warming effect of SSTs. In this context, Grew developed a simplified global climate model, Climate Function, for the use of conceptual design of SSTs.[23] This model can predict future surface temperature change caused by SST fleet's emissions.

The global warming due to water vapor emission is a non-negligible problem for LH_2 SSTs which will emit much more water vapor than conventional kerosene SSTs. Therefore, this study applies Climate Functions for the use of LH_2 SSTs with reasonable assumptions. This will be explained in Section 4.1.1.

The evaluation methods of environmental impacts were validated with the data of Concorde and Olympus 593. (not shown in this paper)

3 LH_2 SST

3.1 General Characteristics

The fundamental differences between kerosene and hydrogen are compared in the Table. 3.1.[25]

One of the notable differences is the energy density per unit weight of hydrogen which is higher than that of kerosene. Accordingly, the necessary fuel weight of hydrogen aircraft for the same mission will be reduced by one-third. This is one of the outstanding advantages of hydrogen fuel.

On the other hand, the energy density per unit volume of hydrogen is 0.25 times lower than that of kerosene. Accordingly, the necessary hydrogen fuel volume for the same mission will be increased by four times.

The tank of hydrogen aircraft is different from that of kerosene aircraft in structure because of the chemical characteristics of hydrogen fuel. Hydrogen is liquefied at extremely low temperatures. In order to maintain its liquid state, the hydrogen tank requires a thermal insulation wall. Moreover, in order to prevent ambient air from entering into, the hydrogen tank has to be pressurized over 1.0 atm at least for ground operation, which is higher than the conventional cabin pressurization of 0.8 atm. Ideally, the hydrogen tank will have a cylindrical shape which receives the pressurization loading. Such a cylindrical tank will be installed not in the wing but in the fuselage. For these reasons above, a liquid hydrogen tank would be much heavier than that of kerosene tank. According to the study of hydrogen-fueled SST by NASA [3], the tank was conceptually designed at 21.5 K and 1.5 atm, which was estimated to be 24% of the fuel weight. Although the tank weight accounts for a relatively large portion of the total weight, the takeoff weight was reduced by 50% compared to the reference kerosene-fueled SST. This was due to the 75% reduction in the fuel weight. In the study of subsonic transport by EU [4], such a large takeoff weight reduction was not confirmed. Thus, one can say that, from the perspective of weight reduction, the application of hydrogen fuel is suitable for SST which stores a large amount of fuel.

In the combustion room of engine, hydrogen fuel is burned in gaseous while kerosene fuel in liquid. Gaseous fuel can avoid the creation of local rich zones where NOx formation tends to occur. Furthermore, the flammable range of hydrogen is wider than that of kerosene so that the lean burn of hydrogen can be achievable. For these reasons, hydrogen aircraft will emit less NOx. However, the evaluation method of NOx emission in this study cannot take these phenomena into accounts.

In addition, the combustion of hydrogen produces no CO_2 but 2.6 times more H_2O per unit energy under the assumption of complete combustion. As mentioned in Chapter 1, water vapor emission which may lead to global warming is one of the concerns of SST. Although there are a lot of unknowns concerning the effects of water vapor emission at the stratosphere, the climate change impact should be considered in the application of hydrogen fuel. This study considers it by using Climate Function proposed by Grew. [23]

3.2 Basic Performances of LH_2 SST

The engine and aerodynamic performances of LH_2 SST are evaluated in this study.

In this evaluation, a pure turbojet was used for the comparison between kerosene and hydrogen fuel as shown in Table 3.2.[8] The jet velocity of a hydrogen engine was increased by 2.9% because the average molecular mass of emission gas was decreased, so that the speed of sound was also increased according to Eq. (3). The thrust was increased by 3.6% due to the increased jet velocity. The specific fuel consumption was reduced by 63.9% because of the slightly increased thrust and the markedly decreased fuel flow.

$$a = \sqrt{\frac{\gamma RT}{\bar{M}}} \quad (3)$$

A conventional tube and wing geometry was used for the comparison of three different fuselage volume as shown in Fig. 3.1. [8] Among several performances, the difference in fuselage friction stood out more as shown in Fig. 3.2. [8] As mentioned in Section 3.1, one can expect that the advantage of a hydrogen-fueled aircraft would be expanded by increasing the amount of fuel. However, it results in larger fuselage volume and it is necessary to pay attention to the increment of fuselage friction drag.

4 Comparisons between LH_2 and Kerosene

4.1 Global Analysis

4.1.1 Introduction

In Chapter 3, the engine and aerodynamics performances of LH_2 SST are evaluated. In Section 4.1, the aircraft performances and the environmental impacts of LH_2 SSTs are evaluated in comparison with those of kerosene SST. The evaluations are made in a design space which is defined by nine design variables.

In this paper, the authors analyzed the evaluation items (the aircraft performances and the environmental impacts) in the following methods.

First, samples extracted from the above design space are analyzed by using Self-Organizing Map (SOM) [26] which is a data-mining technique to classify the samples by similarity. This method can extract information about the relationships between design variables and evaluation items. Second, optimal solutions from the above design space are analyzed. The detail of the optimization will be explained later.

In order to make a fair comparison between LH_2 SST and kerosene SST, preconditions are set carefully as shown in Table 4.1. The fuel weight and fuselage volume of the kerosene SST is given in reference to Concorde. Then, in order to give the same energy content to both the SSTs, the fuel weight of the LH_2 SST is determined. The additional components, fuel tank and supply system, are considered in the weight estimation in reference to the previous study of NASA [3]. The amount of the emission gas is also considered according to the composition (hydrogen: H_2, kerosene: $C_{12}H_{23}$). The price of both fuels is given in order to evaluate direct operating cost (DOC). This study assumes that both fuels have the same fuel price per unit energy.

4.1.2 Analysis on the Relationships between Design Variables and Evaluation Items

The analysis was performed using the same design space as the previous study [8], as shown in Table 4.2. In order to cover the entire range of the design space, 150 samples were extracted by using Latin Hypercube Sampling method. The nine evaluation items were monitored.

The most interesting relationship is one between cruise altitude (ALT) and direct operating cost (DOC). For the SOM of kerosene SSTs, lower DOC solutions which are located at the upper left region have ALT of about 50kft as shown in Fig. 4.1 (a). On the other hand, for the case of LH_2 SSTs, lower DOC solutions have ALT of more than 56kft as shown in Fig. 4.1 (b). Behind this background is the fact that there is an optimal altitude which maximizes lift-drag ratio at a given wing loading as shown in Eq. (4-6). Eq. (5) shows the optimum lift coefficient which maximizes the lift drag ratio of Eq. (4). In order to attain the optimum lift coefficient of Eq. (5), one has to set a proper wing loading or a proper dynamic pressure as show in Eq. (6).

$$L/D = \frac{C_L}{K(C_L - C_{L0})^2 + C_{D0}} \tag{4}$$

$$C_{Lopt} = \sqrt{\frac{KC_{L0}^2 + C_{D0}}{K}} \tag{5}$$

$$C_L = \frac{W/S}{0.5\rho V^2} \tag{6}$$

The reason for the difference in the optimum altitude between LH_2 SSTs and kerosene SSTs can be explained by the difference in the wing loading. LH_2 SSTs tend to have lower takeoff weight and larger wing area.

The previous study [5-6] predicted the difference in the optimum altitude qualitatively. On the other hand, this study shows it quantitatively by using SOM.

4.1.3 Analysis on the Optimal Solutions

It is necessary to run an optimization in selecting a better aircraft from a global design space. In this paper, the two design goals were adopted: minimizing DOC and minimizing climate change impact (ΔT). DOC is often used as a metric of aircraft. ΔT was adopted as a goal since the specific target value of ΔT has not yet been established. The same nine design variables were used (see Table 4.2). The seven design constraints were given as shown in Table 4.3. Each constraint values were given with reasonable assumptions. This optimization utilized the optimization algorithm of NSGAII and the iteration was conducted until convergence.

From Fig. 4.2 which shows the pareto solutions of both SST, one can see that the LH_2 SSTs tend to have larger ΔT as expected. However, it is still possible to select a solution which has the same level of the ΔT as the kerosene SST by sacrificing the DOC.

From Table 4.4 which shows the specifications of pareto solutions of both SSTs, one can see that the takeoff weight of LH_2 SSTs is much less than that of kerosene SSTs while the wing area of LH_2 SST is much larger. Thus, LH_2 SSTs have lower wing loading.

From Table 4.4, one can also see the difference in the active design constraints between LH_2 SSTs and kerosene SSTs. Although the design constraint of airport noise (NOISE) is active for both SSTs, that of the takeoff field length (TOFL) is active only for kerosene SSTs while that of climb capability at initial cruise altitude (ICAC) is active only for LH_2 SSTs. The reasons can be explained by the differences in the wing loading and optimum altitude. LH_2 SSTs have lower wing loading so that they can take off with a shorter TOFL. In addition, as the cruise altitude goes higher, the engine thrust decreases. Therefore, the requirement for ICAC will be strict for LH_2 SSTs.

From Table 4.4, it is also found that the cruise speed of LH_2 SSTs was lowered. This is linked to the requirement for ICAC. In order to produce higher net thrust at cruise altitude, it is rational to reduce ram drag by lowering cruise speed. (Net thrust = gross thrust – ram drag)

4.2 Sonic Boom Analysis

4.2.1 Introduction

In Section 4.1, the aircraft performances and the environmental impacts of LH_2 SSTs were analyzed in a global design space. In Section 4.2, the sonic boom of LH_2 SSTs was analyzed in detail by using a more accurate method (see Chapter 2).

First, in order to establish a reference model, an airframe shape optimization was performed. Next, by using the reference model, the sonic boom of LH_2 SSTs was analyzed in comparison to that of kerosene SSTs.

4.2.2 Airframe Shape Design

The six design variables of fuselage radius NURBS control points and wing planform parameters were used as shown in Fig. 4.3. The design goal is to minimize the sonic boom loudness (PLdB). The base model is the min. DOC solution of LH_2 SST (see Table 4.4). By optimizing the design variables manually, a low boom design was obtained and designated as a reference model.

4.2.3 Analysis on the Reference Models

Sonic booms are affected by the altitude, speed, weight, and length of aircraft. The lower mass density and higher energy density of LH_2 make a difference in aircraft's size and weight. The effects of these differences on the sonic boom's loudness were compared.

The airframe of both SSTs was based on the same reference model. The airframe shape of the kerosene SST was shrunk according to fuselage volume. It is found in Section 4.1.3 that LH_2 SSTs have lower wing loading. According to Eq. (6), the lowered wing loading decreases the dynamic pressure if the lift coefficient is constant. The dynamic pressure is decreased by increasing altitude. Our motivation is to see how much the difference in altitude will have effects on sonic boom loudness. From Fig. 4.4 which compares the signatures at the same lift coefficient of 0.1, it is found that LH_2 SSTs can fly higher so that the sonic boom is quieter by 2.2 PLdB due to the altitude decay effect. The results are summarized in Table 4.5.

4.3 NOx Emission and Airport Noise

4.3.1 Introduction

In Section 4.1, the NOx emission and airport noise was evaluated in a simple way. In Section 4.3, those are discussed in detail.

4.3.2 NOx Emission

It is expected that LH_2 engines will emit less NOx emission than kerosense engines for two reasons: gaseous combustion and wide flammability range. Gaseous combustion can make the temperature distribution of combustion room be uniform. With wide flammability range, lean combustion can be achieved. In the previous paper [8], the authors showed that flame temperature at the primary combustion zone can be reduced by 600 to 1500R.

In order to exploit the favorable characteristics of H_2 combustor, the combustor needs to be re-designed compared with the conventional designs using regular diffusive combustion. One of the potential candidates is the micromix combustor.[27]

4.3.3 Airport Noise

In Section 4.1, only the sideline noise was evaluated. In FAR36, the airport noise of aircraft is evaluated at 3 measurement points: sideline, approach and cutback. In the previous paper [8], the authors showed the sideline noise of LH_2 SSTs will be increased by 1.3 EPNdB because the jet velocity of LH_2 SSTs increases.

It is expected that conventional SSTs climb much more slowly than subsonic transports, so its cutback noise will be much louder. However, LH_2 SSTs will reduce cutback noise because of its shorter TOFL performance.

5 Feasibility of LH_2 SST

In Chapter 5, the feasibility of LH_2 SSTs is discussed on the basis of the results of Section 4.1-4.3.

As discussed in Section 4.1, it is found that the active constraints of LH_2 SSTs are the airport noise requirement (NOISE) and the climb capability requirement at initial cruise altitude (ICAC). There are two methods to improve the ICAC performance: one is to reduce the cruise speed for reducing ram drag and the other is to change engine cycle for cruise condition. The former is a practical solution. For the latter, new propulsion technology needs to be developed such as a variable cycle engine.

Furthermore, it is found that LH_2 SSTs tend to have larger global warming effect (ΔT). However, it is still possible to select a solution which has the same level of the ΔT as the kerosene SSTs by sacrificing the DOC.

As discussed in Section 4.2, the sonic boom of LH_2 SSTs will be reduced by about 2 PLdB due to the altitude decay effect. However, it is required to reduce the sonic boom more. Therefore, low boom technologies as to airframe need to be developed as ever.

As discussed in Section 4.3, the NOx emission of LH_2 SSTs will be reduced significantly if a combustor for H_2 can be developed.

As for the airport noise, the sideline noise will be increased by about 1 EPNdB because the jet velocity of LH_2 SSTs increases. On the other hand, the cutback noise will be reduced because LH_2 SSTs can take off more shortly so that the noise level will be reduced according to the distance between the measurement point and the source of noise. Since the cutback and approach noise are yet to be analyzed quantitatively in this study, these items should be considered in the future.

It is necessary to continue to study alternative fuels for not only subsonic jets but also SSTs. Among them, LH_2 SSTs have outstanding features in takeoff weight and takeoff performances (TOFL and SSC). However, there still remain challenges to be solved. These challenges, mainly as to environmental impacts, should be tackled from the perspectives of both airframe and propulsion.

6 Conclusions

In this paper, a global analysis on LH_2-fueled SSTs was conducted in comparison to kerosene SSTs. Then, key technologies for improving the feasibility were discussed.

In Chapter 2, our conceptual design environment which was developed for the airframe and propulsion integration was shown.

In Chapter 3, the general characteristics of LH_2 aircraft were discussed including fuel, tank, combustion, and emission. Then, the basic performances of LH_2 SSTs as to engine and aerodynamic were also discussed. One of the notable features is that from the perspective of weight reduction, hydrogen fuel which has higher energy density than kerosene fuel is suitable for SSTs which stores a large amount of fuel.

In Chapter 4, the aircraft performances and the environmental impact of both SSTs were also evaluated. In the global analysis, the relationship between design variables and evaluation items were analyzed. The result of Self-Organizing Map showed that the altitudes for minimizing direct operating cost of both SSTs are different. In particular, the optimum cruise altitude of LH_2 SSTs will be higher than that of kerosene SSTs. In addition, the result of multi-objective optimization showed several important differences. Among them, the authors revealed the active constrains of LH_2 SSTs and kerosene SSTs: airport noise and climb capability at cruise altitude for LH_2 SSTs and airport noise and takeoff field length for kerosene SSTs. Furthermore, the environmental impacts of LH_2 SSTs were discussed including sonic boom, airport noise and NOx emission.

In Chapter 5, the feasibility of LH_2 SSTs was discussed. Methods to improve cruise altitude climb capability which will be an active constraint for LH_2 SSTs were suggested. In addition, suggestions were made for improving other performances including climate change impact, sonic boom, airport noise and NOx emission.

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Table 3.1 Fuel Property [25]

		Liquid Hydrogen	Gaseous Hydrogen	Jet A
Composition		H_2		$C_{12}H_{23}$
Molecular mass		2.016		168
Energy density	kJ/g	120		42.8
Mass density	kg/m3	71	0.09	811
Specific heat	kJ/kg/K	9.69	14.3	1.98
Boiling temp.	K	20.27		440-539
Melting temp.	K	14.1		233
Vaporization heat	J/g	446		360
Cooling power	kJ/g	> 16.9		0.39
Flammable range	%	14 - 250		52 - 400
Ignition energy	mJ	-	0.019	0.2-0.3

Table 3.2 Engine Performance [8]

		Kerosene	LH_2
Altitude	ft	1000	1000
Speed	M	0.35	0.35
mass flow	lb/s	504	504
TIT	R	2640	2640
OPR	-	15.2	15.2
p3	psia	232	232
T3	R	1241	1241
Fuel flow	lb/s	10.1	3.8
FN	lb	38400	39800
SFC	lb/lb/hr	0.94	0.34
Vj	ft/s	2740	2820

Table 4.1 Preconditions for Designing SSTs
(See the fourth paragraph of Section 4.1.1 for more detail)

		Kerosene	Hydrogen
Fuel capacity	klb	200	71.4
Fuselage Volume	kft^3	12.5	30
Tank weight	lb	0	$0.24\times W_{FUEL}$
Fuel supply system weight	-	1.00	1.84
Water vapor emission	-	1.0	2.6
CO_2 emission	-	1.0	0.0
Fuel price	-	1.0	3.0

Table 4.2 Design Variables for Global Analysis

		Lower	Upper
Altitude	kft	45000	65000
Speed	Mach	1.5	2.0
FN	lb	25000	35000
BPR	-	1.5	2.5
CPR	-	6.0	8.0
TIT	R	2500	3000
Wing area	kft^2	3.0(6.0)*[1]	5.0(10.0)*[1]
L.E. sweep angle	deg	45	65
T.E. sweep angle	deg	-10	10

*[1] Values in the parenthesis is for LH_2 SSTs

Table 4.3 Design Constraints for Global Analysis

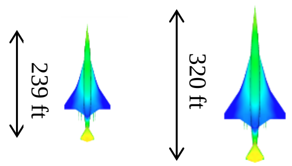
			Limit	Comment
SSC	-	>	0.03	Minimal takeoff climb capability (FAR25)
TOFL	ft	<	10000	Typical takeoff distance of international airport
ICAC	ft/s	>	0	Minimal cruise climb capability
RANGE	nm	>	3500	Range performance (Concorde: 4000nm)[28]
ΔP	psf	<	2.25	Pressure rise of sonic boom (Concorde: 2.00psf)[29]
EINOx	g/kg	<	15	NOx emission (Concorde: 23g/kg)[30]
EPNL	EPNdB	<	100	Sideline noise level (Concorde: 120EPNdB)[31]

Table 4.4 Optimums extracted from Pareto Solutions

		Kerosene SSTs		LH_2 SSTs		
		Min. ΔT	Min. DOC	Min. ΔT	Min. DOC	Comment
Altitude	[ft]	49160	50457	50979	53944	Higher altitude
Speed	[-]	1.62	1.65	1.57	1.56	Lowered speed
FN	[lb]	29921	28308	30010	30021	
BPR	[-]	2.02	2.06	2.09	2.03	
CPR	[-]	6.58	7.09	7.23	7.18	
TIT	[R]	2720	2734	2644	2649	
Wing area	[ft^2]	4244	4332	7470	7307	Enlarged wing area
L.E. sweep angle	[deg]	56.3	58	56.5	56.5	
T.E. sweep angle	[deg]	-3	-2.1	1.5	0.7	
RANGE	[nm]	4486	4711	4513	4809	
ICAC	[ft/s]	46.5	41.2	14.8	0.1	Active constraint for LH2 SSTs
TOFL	[ft]	9960	9940	3921	3975	Active constraint for kero. SSTs
SSC	[-]	0.041	0.038	0.169	0.168	
NOISE	[EPNdB]	98.9	98	98.1	98.2	Active constraint for both SSTs
EINOx	[lb/klb]	10.6	12.9	11.1	10.5	
ΔP	[psf]	2.19	2.2	2.2	1.97	
Max. takeoff weight	[lb]	403872	401554	332917	332665	Weight reduction
Empty weight	[lb]	175404	173086	233064	232811	
Fuel weight	[lb]	200000	200000	71400	71400	

Table 4.5 Summary of Sonic Boom Analysis

		Kerosene	LH_2	Comment
Speed	Mach	1.57	1.57	
Altitude	ft	39200	51000	
Cruise weight	lb	308000	306000	50% fuel consumed
Length	ft	239	320	
Wing area	ft^2	4240	7470	
Wing loading (W/S)	lb/ft^2	72.6	41	
CL	-	0.1	0.1	
Sonic boom loudness	PLdB	96.3	94.1	
Airframe				



Balanced Goals for Practical Civil Supersonic Aircraft (Technology Available)	N+1 Supersonic Business Class Aircraft (2015)	N+2 Small Supersonic Airliner (2020)	N+3 Efficient Multi-Mach Aircraft (Beyond 2030)
Design Goals			
Cruise Speed	Mach 1.6-1.8	Mach 1.6 -1.8	Mach 1.3 - 2.0
Range (n.mi.)	4000	4000	4000 - 5500
Payload (passengers)	6-20	35-70	100 - 200
Environmental Goals			
Sonic Boom	65-70 PLdB	85 PldB (Revised)	65-70 PLdB Low Boom flight 75-80 PldB Overwater flight
Airport Noise (cum below stage 4)	Meet with Margin	10 EPNdB	10-20 EPNdB
Cruise Emissions (Cruise NOx g/kg of fuel)	Equivalent to current Subsonic	< 10	< 5 & particulate and water vapor mitigation
Efficiency Goals			
Fuel Efficiency (pass-miles per lb of fuel)	1.0	3.0	3.5 – 4.5

Fig.1.1 NASA N+3 Target [1]

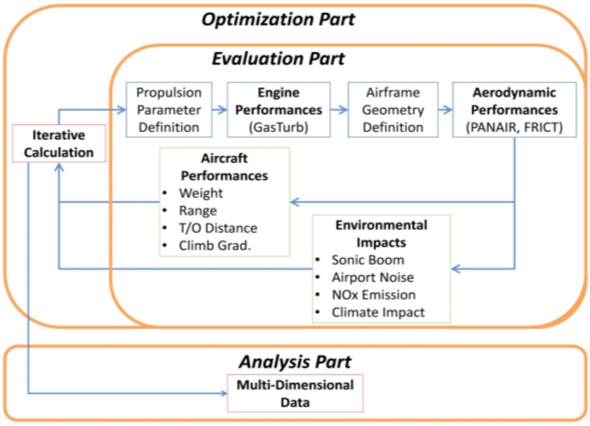


Fig. 2.1 Conceptual Design Environment [7-8]

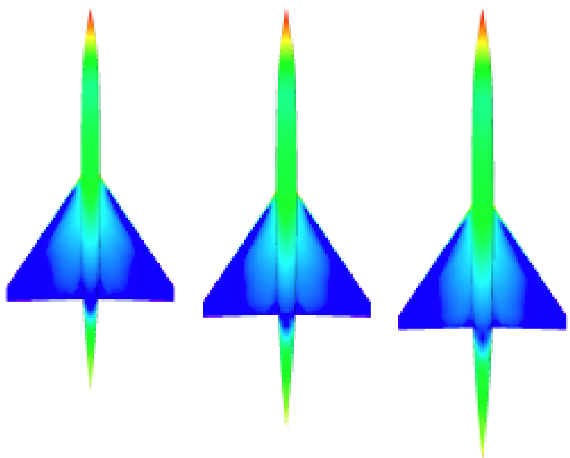


Fig. 3.1 LH2 SSTs with Different Fuselage Volumes (30k, 40k, 50kft^3) [8]

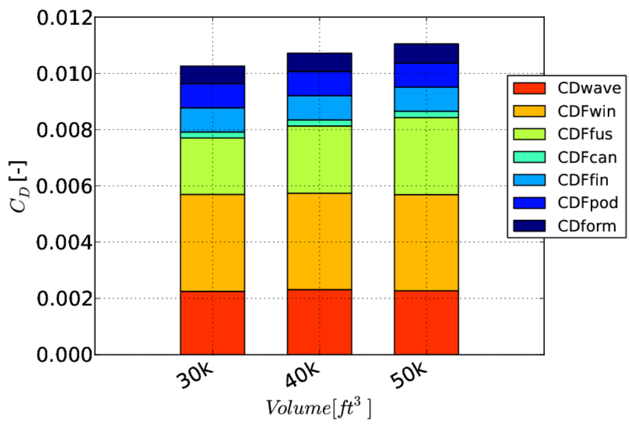
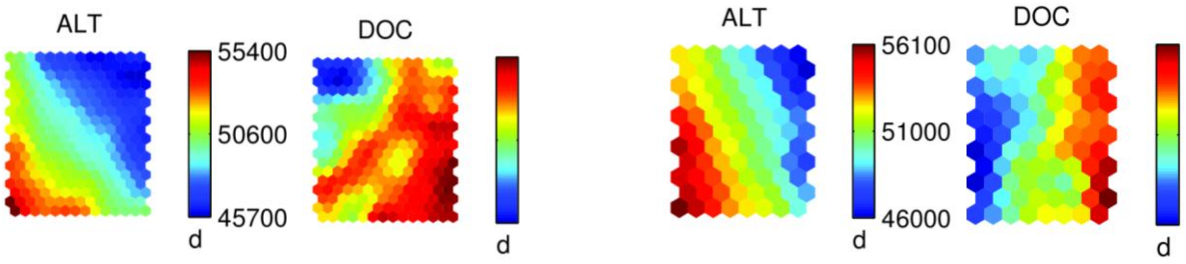


Fig. 3.2 Drag Components (30k, 40k, 50kft^3) [8]



(a) Kerosene SSTs (b) LH_2 SSTs

Fig. 4.1 SOM as to Cruise Altitude (ALT) and Direct Operating Cost (DOC)

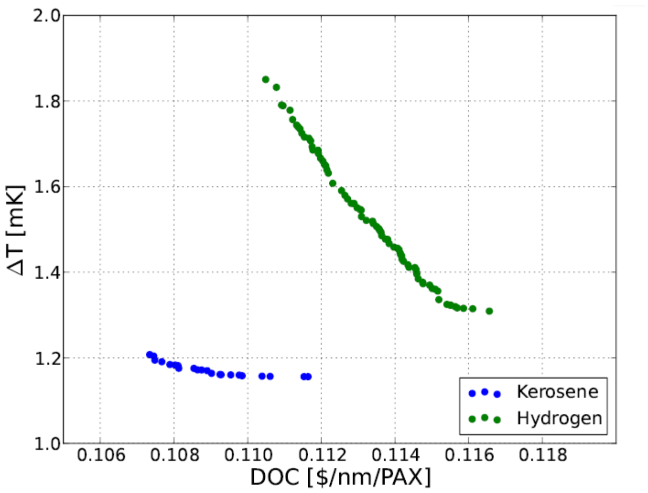


Fig. 4.2 Pareto Solutions [8]
(See also Table 4.3)

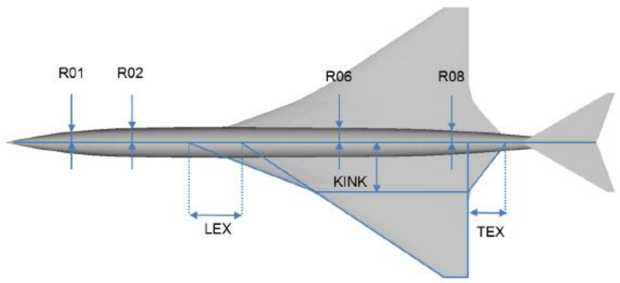


Fig. 4.3 Design Variables for Sonic Boom Analysis (Airframe Shape Design)

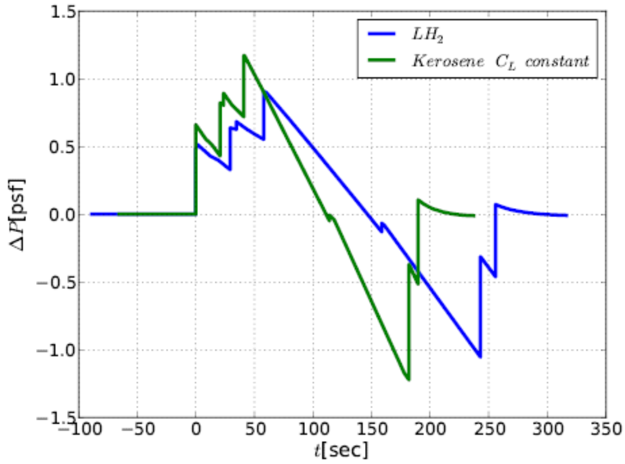


Fig. 4.4 Sonic Boom Signatures [8]
(See also Table 4.4)