PROMISING FUTURE AIRCRAFT CONCEPT - ESTOL

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Abstract[1]

A severe problem seen in the US as well as in Europe is the upcoming capacity shortage of major hub airports. The lack of capacity regularly results in longer taxi and loiter times today. Though the US and Europe, both have a very dynamic air transport market; however in an international comparison these markets are quite mature. It is expected that the real growth in the next decades will mainly take place in Asia, especially in China and India. Taken into consideration that the European Commission expects air traffic to double in the next 20 years [2], the following question arises;
What type of aircraft will meet best the future market requirements and therefore will prevent the Asian air transport market running into the same problems Europe and the US already face today?
In this paper the potential of currently proposed solutions to airport capacity problems will be analyzed. Thereafter it will be discussed to what degree an extreme short take-off and landing (ESTOL) aircraft possesses the capability to overcome the capacity problems. Consequently such ESTOL concepts will be introduced and the aircraft conceptual design phase will be described. Finally the results will be presented and discussed.

1 Introduction

360 million Chinese will be expected in the global middle class by 2030 [5]. The average traffic growth is said to be around 11% until 2020 and today there are already three hubs with over 30 million passengers per year. This amazing growth can only be successfully handled in the light of the following three factors: The surge in oil prices, the currently emotionally debated climate impact of aviation and the imminent airport capacity shortage. These limiting constraints are not only representatively valid for the growth in China, but also for the western countries.

2 Status quo, problems and trends in air transportation

Looking at the US, it is undeniable that most hub airports are already operating at their capacity limit. 22 major US airports are predicted to suffer from capacity shortage for the next two decades, according to FAA (2007). While the situation in Europe is quite similar to the US, the growing middle class of emerging countries will further increase the demand for mobility considerably by 2030 [4]. Additionally, freight and business travel will increase at even higher pace, thus demanding for (high end) ‘mega city’ connections. The Chinese airport development in contrast, has been much slower than the air traffic growth. Only four out of 142 airports in China have the ability to handle air traffic under (almost) all weather conditions (ILS CAT II). As a consequence the Chinese air traffic will face the same problems as the western countries soon if no effective and sustainable solutions will be proposed.

2.1 Analysis and summary of currently proposed methods

[1] Thanks to my colleagues Dr. Kuhlmann, Dr. Kelders, Mr. Steiner, Mr. Gologan and Mr. György for their contribution.

Two of the many more proposed solutions will be summed up and analyzed.
The use of larger aircraft is believed to alleviate the capacity shortage. But it has to be stated clearly that airliners use larger aircraft only when it comes to be a profitable business and not to increase the 'system' capacity [5]. According to [9], the past growth has not necessarily lead to bigger airplanes. In contrast, slightly smaller ones are preferred, because of the faster turnarounds and thus increased utilization and amount of legs and a smaller noise foot print.
The implementation of new runways or even airports will surely help. On the other hand it is a well known fact how difficult the realization of any runway extension can be. Even by passing through environmental and political challenges, adding capacity can be a very slow and cost intensive process. Furthermore airport extensions are often limited by physical boundaries, like geographical hindrances or the growth of the city. Political incentives are not to underestimate, as governments are willing to sacrifice investments at congested airports for others with reference to regional development goals.
Therefore it is very likely to fall short of the traffic demand with the above argumentation.

2.2 ESTOL recommendation

Since the bottleneck at hub airports is due to the limited space on the main runways [3], a new approach is giving airliners the technical possibility to meet the excess demand with ESTOL capable aircraft allowing the more efficient usage of scarce infrastructure.
The research efforts at Bauhaus Luftfahrt showed a possible way to increase capacity; a rearrangement of existing runway area and using an ESTOL and conventional take-off and landing (CTOL) capable aircraft. Comparable research work was conducted by the national aeronautics and space administration (NASA) and they concluded a significant increase in capacity and delay reduction is possible by the introduction of ESTOL jets with new approach procedures [11].

Fig. 1. General airport layout with two additional ESTOL runways

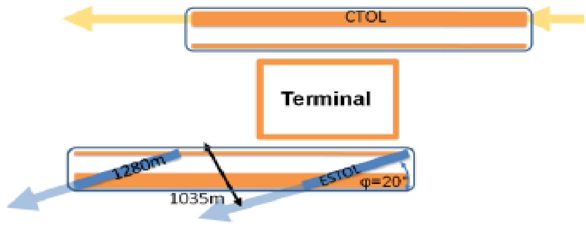

Fig. 1 depicts a double ESTOL runway layout, which could be operated independently and at the same time the CTOL runway could be used for e.g. bigger / long haul aircraft [5]. This research project is still not finished yet, as the new arrangement will be combined with new approach procedures to ensure the increased capacity. In addition to technical feasibility, the economical aspects are also presented in [5].
ESTOL aircraft have the potential to offer a viable solution to airport congestion, capacity and community noise concerns [12]. And as a hub-feeding transport system, it will be attractive for transfer and time sensitive passengers [4].
According to the results above, typical mission requirements for an ESTOL regional jet are derived in [5] and summed up in Table 1.

Table 1. ESTOL regional jet requirements

Take-off field length	[m]	1000
Range	[nm]	1200
Cruise mach number	[-]	0.78
Cruise altitude	[ft]	37,000

3 Aircraft conceptual design

This chapter describes the process and methods used to generate a possible aircraft design to meet the above mission requirements.
Based on the fact of the necessity to face the capacity shortage and the environmental aspects at the same time, a combination of different technologies might help – the ESTOL capability to face the capacity shortage and a new lifting surface concept, which could 'absorb' the inherent fuel penalty of the ESTOL jets. This project is known as 'Hybrid Airliner' (HyLiner) at Bauhaus Luftfahrt.

3.1 Lifting surface configuration

Three different kinds of unconventional lifting surface configurations were analyzed, as they seem to have superior aerodynamics and to some extent even better weight performances than conventional ones. Strut-braced wing, box wing and joined wing are in scope of this analysis.
Because of the wider and broader data basis, the joined wing lifting surface configuration was chosen (Fig. 3).
According to [10] wind-tunnel tests and finite-element structural analysis have shown the following advantages compared to conventional configurations: Lighter weight and higher stiffness, higher span-efficiency factor, lower drag and direct side-force control capability.

3.2 High lift systems for ESTOL

For an ESTOL concept conventional leading and trailing edge slats and flaps are not appropriate. Hence high lift systems used for military transport aircraft, such as C-17 and YC-14 were considered.

Fig. 2. Blown flaps high lift systems [8]

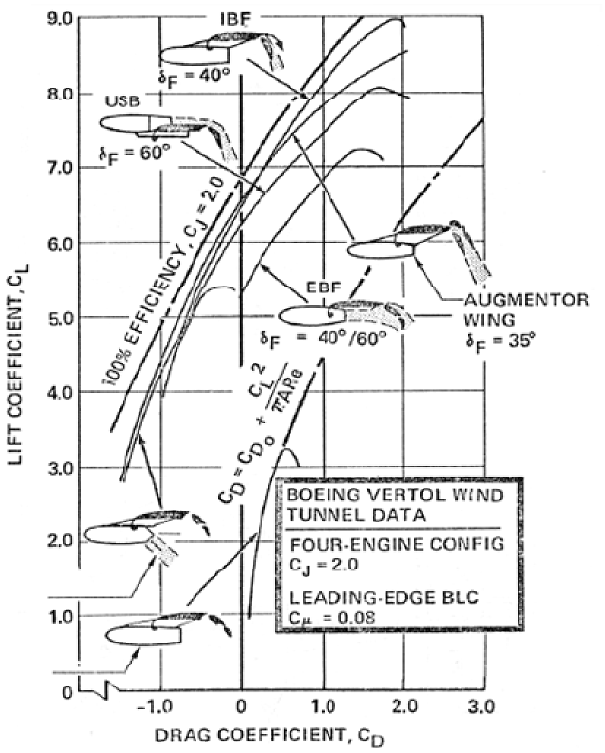

Fig. 2 depicts the different high lift systems and their maximum lift coefficient.

Care was taken to adequately convert these two dimensional profile lift coefficients to three dimensional configurational ones, later on.

3.3 Finding the concepts

Having frozen the lifting surface configuration and shown the alternatives of high lift systems, it is necessary to find the concepts to go on with a parametric design study. In a matrix of alternatives (MoA), the theoretical maximum amount of combinations of these single technologies result in a multiplicity of potential concepts. A reasonable amount of concepts was then reached through a qualitative assessment. Table 2 represents the main characteristics and parameters after the assessment process.

Table 2. Main characteristics

Component	Characteristics
Joined wing	Variable
High lift system	Internally blown
	Upper surface blowing
Aspect ratio	Variable
CL_front wing	Variable
CL_rear wing	Variable

Typical design equations for the different mission phases were adapted to the joined wing concept to start the calculation process. Lift coefficients were seen as input values, which will be verified in a next step after defining the geometry. Since these parameters are not fixed, but varying in a given range, each combination of the parameters represents a new configuration. Though the difference between each adjacent configuration might not be significant, it is believed to find the most promising configuration by doing so. Fig. 3 represents the three most promising concept types, which were analyzed in more detail[2].
Preliminary mass estimations were done with handbook methods[3]. Other input values e.g. parasite drag were obtained from the reference aircraft, Embraer ERJ 145.

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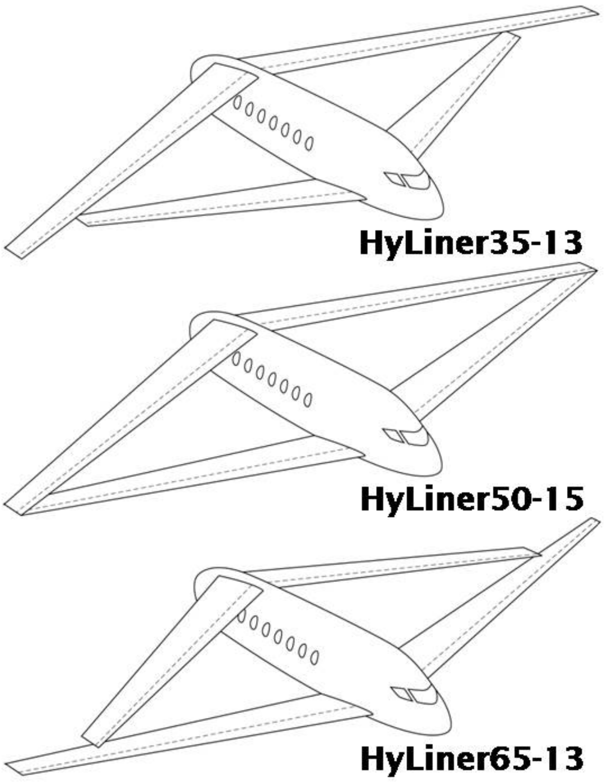
[2] In this figure high lift system are not pictured, as they are representing the roughly geometrical proportions of the concepts.
[3] Equations for the calculation of the structural mass are taken out from [6].

As a result of the first calculation iteration the aircraft geometry could be determined. With them the lift coefficients needed for the ESTOL capability could be verified in dependence of span geometry and used high lift system.

Fig. 3. Aircraft concepts with different wing joint positions



[4]

Thereafter a more exact structural and fuel mass calculation could be done. The mission was divided into engine start, take-off to an altitude of 35ft, first climb segment to 400ft, climb to cruise altitude, cruise, descent, loiter and the flight to an alternative airport. The effective cruise distance depends upon the covered distances during climb and descent phases. Calculation steps for the climb phase were defined by every 500m in altitude. A new actual mass will then be calculated in dependence of the ratio of acceleration and climb power. During cruise ten calculation steps were designated.

A more detailed estimation of the lifting surfaces mass was done and will be presented in the coming chapter.
By freezing the geometry of the configurations a drag analysis was done and will be presented in chapter 5.

4 Lifting surface mass estimation

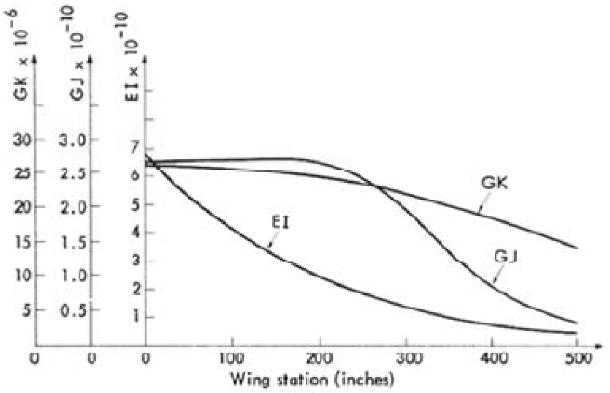
One of the superior advantages of the joined wing lifting surface concept is said to be the lighter overall weight and higher stiffness.
Since the equations used to calculate the structural weight are based on empirical aircraft data, it is most probable that these lifting surfaces are oversized than comparable conventional wings. This is because of the more slender wings, each with a comparable higher aspect ratio.
On the other hand it seems to be intuitionally clear that with this concept a higher overall stiffness could be reached. The wings are connected with each other at the joint position and at the front and rear fuselage. Additionally, another load bearing behavior can be expected for this system.
However at the time the analysis took place, there were no formulas found for wing mass calculation taking these aspects into account.

4.1 Approach and used methods

For given load cases, the lifting surface deformation was calculated by a finite-element analysis. Considered load conditions were 1g and 2.5g for trimmed cruise flight. The calculation was done with NASTRAN. The doublet lattice method was used to determine the aerodynamic loads.
Since the exact structural layout of the profile cross sections was not defined, a typical bending stiffness distribution (see Fig. 4) was assumed. This assumption was based on modal analysis of the lifting surface concept, where the first typical eigenmode was assumed to be around 3Hz.

[4] The first two digits represent the front lifting surface area referred to the total reference are and the last two digits describe the aspect ratio of the lifting surfaces. Currently it is assumed that both lifting surfaces have the same aspect ratio.

Fig. 4. Bending, torsional and shear stiffness distribution [1]



The resulting deformations were qualitatively checked for their plausibility.
The bending stiffness consists of two factors. The 'Young´s modulus' (E) is a material dependent factor and the geometrical moment of inertia (I) will be calculated through the structural layout of the profile cross section.
E was chosen from typical aluminum alloys.

Fig. 5. Structural layout of the profile cross section

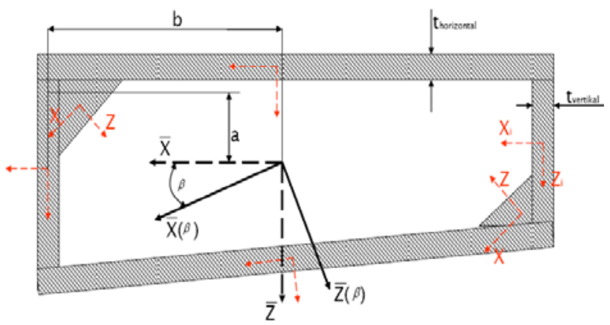


Fig. 5 depicts the profile cross section structural layout of the wing-box for the inverse calculation of I. The triangular areas are necessary to increase the moments of inertia with respect to the twisted bending moment axis.
To ensure that the structure can fulfill the assumptions, three sections alongside the span were chosen for the inverse calculation, namely root, joint position and tip for each wing. Among these cross sections a linearly dependent distribution reduction of I alongside the span was assumed. This means that to some extent a safety margin was provided, since the real characteristic is a non-linear reduction.

Table 3. Lifting surface primary structure mass

HyLiner35-13	2,188kg
HyLiner50-15	2,243kg
HyLiner65-13	2,341kg

Table 3 shows the structure mass of the lifting surfaces of the three configurations based on the above described calculation. Interestingly this result is still higher than that of the reference aircraft. On the other hand there is definitely still potential for weight improvements as aluminum alloys were used and a safety margin was considered.

5 Results and conclusions

According to the process described in the previous chapters, a summary of the results concerning mass and drag breakdown, as well as the 'L over D' (L/D) characteristics of the configurations will be presented and discussed.

5.1 Mass breakdown

Fig. 6 depicts the component masses of the different aircraft including the mission fuel mass. The maximum take-off mass (MTOM) of these aircraft are shown in Table 4.

Fig. 6. Mass breakdown

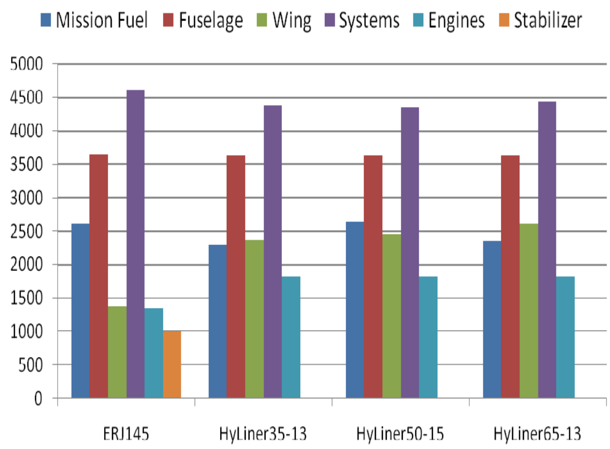


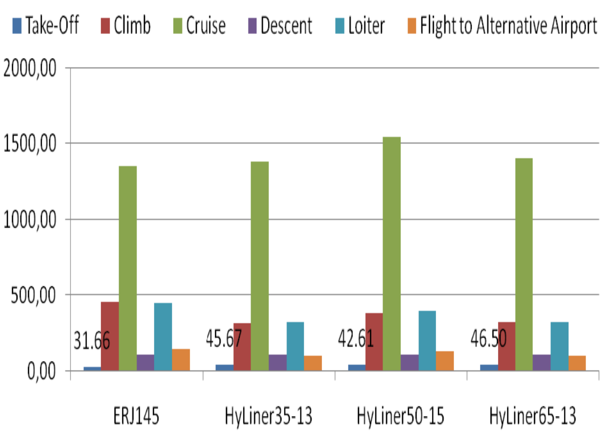
Table 4. MTOMs

ERJ145	21,000kg
HyLiner35-13	19,915kg
HyLiner50-15	19,808kg
HyLiner65-13	20,183kg

Interestingly none of the presented ESTOL configuration exceeds the MTOM of the reference aircraft, but this is due to the non-existence of the vertical stabilizer. In a first step it was assumed that the direct side force capability will ensure the controllability. On the other hand the wing weight is much higher than the conventional configuration, though they are not that much away from the results of Table 3[5]. Thus considering the improvement potentials it seems to be possible to approximately come to the same MTOM range as the reference aircraft, even with a vertical stabilizer.

Looking at the fuel shares, the HyLiner50-15 is the most fuel consuming aircraft among the presented configurations. This can be explained by the worst L/D characteristic of this aircraft compared to the presented configurations (Fig. 9). The comparable bad L/D characteristic is due to the lower aspect ratio. On the other hand there is a significantly higher fuel consumption during cruise, depicted in Fig. 7.

Fig. 7. Fuel burn breakdown



As a result of the ESTOL requirement (Table 1), all presented aircraft have a higher thrust to weight ratio, enabling them to have a faster and shorter climb phase. The climb power depends on the overall overpower. With the higher thrust to weight ratio, the presented configurations are able to climb faster and so to finish the climb phase in a shorter horizontal distance. Consequently, this results in a significantly longer cruise distance and thus higher fuel burn for this mission phase.

The total mission fuel is given in Table 5.

Table 5. Total mission fuel

ERJ145	2,543kg
HyLiner35-13	2,289kg
HyLiner50-15	2,606kg
HyLiner65-13	2,313kg

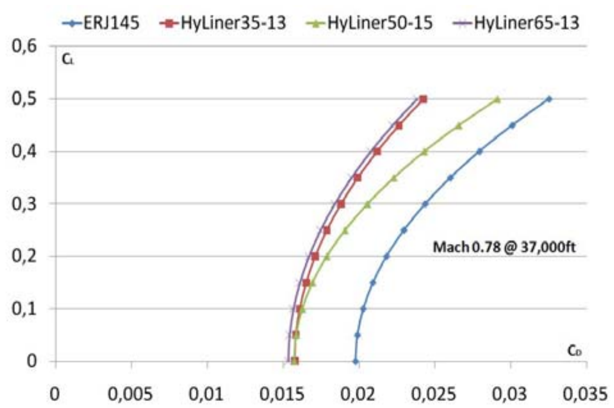
Though in the take-off phase more fuel is typically consumed by the ESTOL jets (see Fig. 7), during the other mission phases the better aerodynamics could alleviate this penalty. To conclude, the mission fuel mass of the presented configurations are still lower than the reference aircraft with exception of HyLiner50-15, which will be explained in the next chapter.

Since CO_2 emissions are directly proportional to the fuel burn, an improvement could be expected as well as a possible reduction of NO_x with new engine technologies. An investigation on limiting the noise foot print only to the airport area is currently performed at Bauhaus Luftfahrt with new approach and departure procedures.

5.2 Drag breakdown and aerodynamics[6]

The drag polar is shown in Fig. 8. Fig. 9 depicts the cruise and maximum L/D for the different aircraft.

Fig. 8. Drag polar for the presented configurations



[5] Results in Table 3 only represent the primary structure mass (wing-box).

[6] Calculation methods for the aerodynamics are based on handbook methods.

The better aerodynamics, seen in the L/D characteristics in Fig. 9 can be explained by the better span efficiency factor [7] and the more slender wings, which generate less friction drag (Fig. 10) due to the shorter lengths. On the other hand L/D is directly influenced by the aspect ratio. Except for HyLiner50-15, the other two presented configurations do possess comparable better aspect ratios[7]. The zero lift drag coefficient is to some extent inverse proportional to the cruise and maximum L/D. Thus an inherently smaller zero lift drag coefficient (Fig. 8) implies a better L/D (Fig. 9).

Fig. 9. L/D characteristics

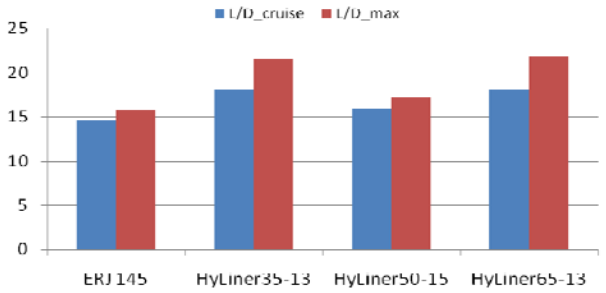
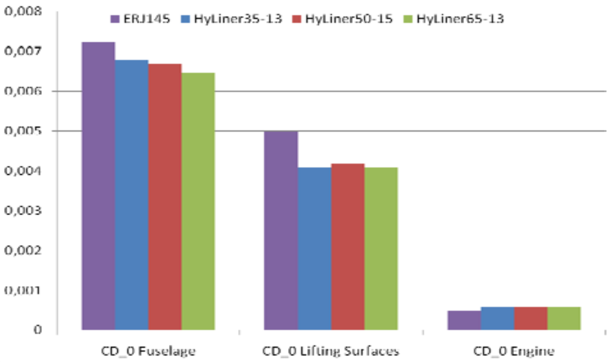


Fig. 10 depicts the parasite drag coefficient shares for the components. The fuselage portions are nearly the same. The aberations between the presented configurations are due to the different wing reference areas. Even with a higher wing reference area compared to ERJ145, a smaller drag share could be obtained by the higher aspect ratio and thus higher wing slenderness. As bigger engines are in charge for the upper surface blown high lift system, the according drag share is higher.

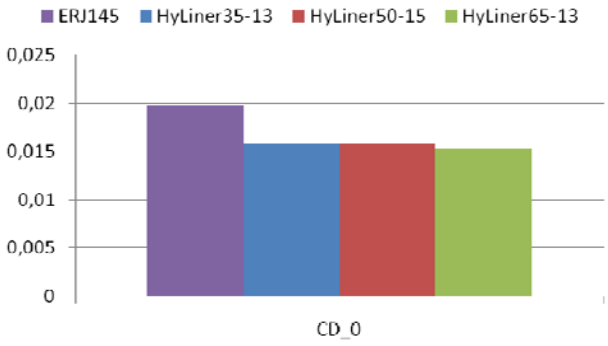
Fig. 10. Component parasite drag shares



[7] The calculation of the aspect ratio was done according to [10] for lifting surface configurations with different span.

The total parasite drag coefficient is shown in Fig. 11. All the presented configurations seem to have a better aerodynamic performance, which in some cases could indeed alleviate the fuel burn penalty of ESTOL capability.

Fig. 11. Parasite drag coefficient



6 Summary and outlook

An ESTOL capable aircraft with CTOL utilizability seems to be a viable solution to face the capacity shortage at hub airports.

The mass calculation shows no significant savings. Compared to the reference aircraft, the lifting surface mass is even higher. The approach with the assumed stiffness distribution and the inverse calculation of the geometrical moments of inertia considered the different load bearing characteristics of those configurations. On the other hand, it has to be recalled, that with the assumption of linear material distribution and aluminum alloys a safety margin is included. Thus further investigations have to be done here to exactly determine the load cases and therefore the mass calculation.

The less total fuel burn is due to the following aspects. First, the lifting surface configuration possesses inherently better span efficiency factor which reduces the induced drag coefficient and hence improve the L/D characteristic. Second, the higher aspect ratios of each wing with smaller chord lengths generate less friction drag. Third, with the higher overall aspect ratios a further decrease in induced drag is possible. All those effects together contribute to the less fuel burn.

As a result of this first calculation phase, it seems that with this lifting surface concept a better aerodynamic characteristic could balance the inherent ESTOL fuel burn penalty. As a

result such an ESTOL configuration becomes really attractive, though there are still many unanswered questions e.g. aeroelasticity, which must be handled in a next step.
Currently there are other research projects at Bauhaus Luftfahrt concerning the airport infrastructure, new approach procedures and other ESTOL concepts to face the future air transportation challenges.

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