PERSPECTIVES OF VERTICAL / SHORT TAKE OFF AND LANDING IN COMMERCIAL AVIATION

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OVERVIEW

Based on an analysis of today's and future transport systems the situation and the potential future development of ground and airborne transportation are described for the most important regions (USA, Europe and China). This investigation concentrates on mid range and short range traffic. According to these demands implications for potential future air traffic systems are derived. Especially in the investigated field a combination of high flexibility and low infrastructure requirement will be essential for the success of new transportation systems. Consequently, a platform with vertical or short take off and landing capabilities (V/STOL) seems to be advantageous. Starting with an evaluation of former and recent approaches to V/STOL (highlighting also the national German programmes in the late 60s) and a description of former achievements and failures potential new solutions will be described. These solutions focus on extreme short take off and landing (ESTOL) with an airplane like platform and on vertical take off and landing (VTOL) with the help of propellers. In addition to the technical features, design characteristics and necessary technology fields, also the economic implications are shown.

1. INTRODUCTION

The commercial aviation industry is changing rapidly. The manufacturing industry went through a major wave of consolidation and restructuring in the late 1980s and 90s and the world airlines had to adapt to new legal frameworks following the liberalisation of the markets. The bilateral relationship between the air framers and the airlines has also changed from a seller's to a buyer's market[1] and the air transport market in turn has faced a strong movement towards more customer-focused business models. After the emergence of the low cost carriers each air transport company has to clarify its own strategy which market segment to serve: one key issue to be resolved is whether an airline is going to be a global network carrier or a player serving a special market segment, focusing either on a geographical market or a particular type of service like holiday charters or the scheduled and/or non-scheduled freight traffic market segment.

But despite this increasing competitive pressure in the industry there is a silver lining of remarkable growth in air transport demand ahead. The latest Boeing forecast predicts a market volume of $2.8 trillion or 28.600 new aircraft over the next 20 years. This will not only imply a replacement of about 80% of the current fleet, but in particular a tremendous increase in the overall market size. To make a simple comparison: a rough estimate of all aircraft that have been sold by Boeing and Airbus in the course of history gives a total value of $1.6 trillion[2]. This increase in market demand is accompanied by a further segmentation of the air transport market, as the recent success of the low-cost airlines shows.

However, so far the increased need for customer focused business models and the impact of the projected high growth rates, which reveal an enormous potential for new aircraft concepts, have not yet been fully addressed. Can (or should) an aircraft only be differentiated by range and passenger capacity like it is usually done or are additional features (like flexibility concerning infrastructure usage) gaining more importance?

Based on these observations, the aim of the current paper is to assess fundamental challenges for future regional transportation systems and to address the question to what extend an aircraft with V/STOL capabilities could contribute to possible solutions to solving some of the upcoming problems. The paper is structured as follows: first, some major global trends are discussed before entering an analysis of developments of regional transport systems (US, Europe and China). Based on this analysis some future demand patterns are derived. In the next step, the potential of VTOL and ESTOL aircraft designs to fulfil these demands are introduced and evaluated.

2. RECENT TRENDS AND FUTURE CHALLENGES IN AIR TRANSPORTATION

In this section global as well as regional trends of the (air) transport industry are discussed and related market demand patterns are derived.

2.1. Global Trends

2.1.1. Market Growth and Segmentation

Given the high development costs, established air framers are reluctant to increase the number of aircraft types and families and rather follow an evolutionary approach when designing new aircraft. This approach is understandable especially for established manufacturers since a modified and more customised aircraft type implies a reduction of sales of the other, already predominant aircraft types. However, the mere size of the future market and the upcoming manufacturers in China and Russia might well

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[1] A buyer's market constitutes a market, where the buyer is in a better bargaining position than the seller.

[2] This back of the envelope estimation reflects the total number of aircraft sold by the two leading companies Boeing and Airbus at current market prices.

challenge this approach. To illustrate this point one has to bear in mind the configuration determinants of the aircraft types currently in use: due to the large fixed costs of developing a new aircraft and a corresponding low aircraft demand, the existing aircraft are essentially a trade off between customer requirements and the potential market size. Of course, aircraft, like any other product cannot be fully customised.[3] However, as already illustrated, the optimal customisation might well be changing since market size is growing. There seems to be room for a greater diversification of (viable) aircraft types.

2.1.2. Growing Competition

Another aspect, besides market growth and segmentation, is the change in competition: following the industry consolidation which peaked in 1996 with the takeover of McDonnell-Douglas by Boeing, the two remaining manufacturers Boeing and Airbus have been dominating the market for large civil aircraft. But currently the market is breaking up again, with the former regional jet manufacturers Embraer and Bombardier and new upcoming competitors from China and potentially Russia challenging the two incumbents. This also has an impact on a manufacturer's portfolio choice: when deciding about a new type or a new aircraft family, incumbents have to take the negative effect on the sales of the own predominant products into account - a newcomer has not. As long as the high fixed costs, the corresponding high risk and the necessary experience in aircraft manufacturing has served as a barrier to entry, incumbents have been in general reluctant to introduce new series. Now, facing market entry of other manufacturers, incumbents might have to react strategically in advance to try to keep potential newcomers out of the market. This gains additional relevance, as new organisational concepts of risk-sharing or -shifting towards subcontractors and suppliers have emerged, which has lowered the (formerly high) barriers to entry for potential competitors. In order to face this competitive threat, the incumbent manufacturers will have to focus on customer demand more vigorously. At the same time, this development offers new possibilities for other manufacturers to enter this market.

In the last few years this issue has been addressed by Boeing and Airbus in the long haul segment, where both manufacturers are currently engaging in an increasing number of new programmes. This seems to reverse the trend of a reduction of aircraft types which cumulated in the Boeing McDonnell-Douglas merger. But an equivalent approach has yet to be set up for the increasing regional markets, which have been a major driver in the recent air transport growth.

A similar conclusion can be drawn from the increased competition between airlines and their corresponding need to get their strategy focused. The largest fraction of the current market dynamics is not driven by the established network and charter carriers but by low cost airlines that have entered the market in response to liberalised market access conditions. This new segment is particularly cost-efficient (and accordingly active) in short-range distance travel. Airlines will increasingly try to influence the preliminary design process since the current portfolio of aircraft manufacturers does not sufficiently address the airlines' specific requirements. Both developments act as push and pull factors for a single manufacturer to get his product portfolio right.

2.1.3. Environmental Aspects

Aviation is currently under particular pressure concerning its environmental impact on climate change. The main trigger for this new attention might be seen in the Stern report on climate change in combination with the new IPCC report, which both have stressed the urgency for action concerning a reduced CO_2 production. Together with a potential increase in oil prices, this might foster a differentiation between slower, green, low cost airlines[4] on the one hand and fast business travel on the other hand.

It is very important to note in this context that in some market segments, fuel efficiency is not an aim, but a (major) side condition. How the trade off between fuel consumption and other passenger preferences (like time) has to be solved depends on the market segment to serve. However, every future aviation concept has to bear in mind its environmental impact.

2.2. Regional Trends

2.2.1. Synopsis of Transport Systems

A short overview on economic, geographical and traffic-related facts of selected countries is displayed in TAB 1.

Country	China	France	Germany	UK	USA
Area (land) [1000 sq km]	9.326	546	349	242	9.162
Population [mio] (2007 est.)	1.322	61	82	61	301
GDP (purchasing power parity) [trillion $] (2006 est.)	10,170	1,891	2,630	1,930	13,130
GDP (official exchange rate) [trillion $] (2006 est.)	2,518	2.149	2,872	2,346	13,21
GDP - real growth rate [%] (2006 est.)	10,7	2,1	2,7	2,8	3,2
GDP - per capita (PPP) [$] (2006 est.)	7.700	31.100	31.900	31.800	44.000
Public debt of GDP (2006 est.	22%	65%	67%	42%	65%
Airports total (2006)	486	477	554	471	14858
Airports paved run. total	403	292	332	334	5119
Railways total [km]	74.408	29.085	47.201	17.156	226.605
HSR lines [km]	1.820	1.573	1.300	74	362
Roadways total [km]	1.870.661	951.220	231.581	388.008	6.430.366
Roadways paved [km]	1.515.797	951.220	231.581	388.008	4.165.110
[km] incl. expressway	34.288	10.490	12.200	3.520	75.009

TAB 1. Economic and traffic related facts of selected countries [5].

Comparing the US to Europe it is striking that air traffic infrastructure is highly developed in the US whereas high speed railway (HSR) tracks are relatively rare. Distances are, however, quite large (the total US land area is comparable to China). Europe, in contrast, has a highly developed railway system with particular emphasis on high speed tracks. Given the short distances (compared to the US), rail and road impose a serious competitive pressure on aviation (which is certainly one out of several drivers for severe price competition between European airlines. However, despite a strong political support for HSR tracks in Europe one can observe a slight withdrawal

[3] To illustrate this: Lufthansa currently uses an A300 for travels between Munich and Frankfurt to accommodate the large demand on this route during peak hours. The A300 has certainly not been designed for this mission (162 nm).

[4] Speed reduction (or rather an airplane that is optimised for reduced cruising speed) is one of several possibilities to save fuel consumption [23].

from sparsely populated regions [25].

2.2.2. Europe and the United States

2.2.2.1. Airport Capacity Shortage

A predominant problem in the US as well as in Europe is the imminent capacity shortage of major airports, and probably will remain in the future. Already today many airports suffer from ongoing excess demand, in particular at peak times. At the same time, traffic demand is assumed to increase significantly in the US and in the EU. Even the European Commission expects air traffic to double in the next 20 years [8].

This general increase in demand for air transportation will lead to more specialized short to mid range services, since many more routes will now become profitable for the airlines [18].[5] A part of this increase in demand will thus be served by currently underutilised regional and smaller airports But whether the whole air transport system will be capable of accommodating the forecasted demand can reasonably be questioned. An increase of capacity by building new runways (or realigning existing runways) and related facilities is also necessary. However it is more than doubtful whether this necessary increase in runway capacity will be feasible in the near future (see for example [7]).

Albeit we will most probably see an increase in specialised short to mid range services, the benefits of a hub and spoke system will remain present in the future. Together with the observed concentration of people in urban and metropolitan areas in the US as well as in Europe we are convinced that the current pattern of air transport infrastructure utilisation will remain: *highly congested (hub) airports in the major metropolitan areas and underutilized regional airports.*[6] It should be noted that the increase in demand for short and medium range services is especially large in metropolitan areas with already congested airports[7]. This trend might decrease the number of services between two hubs, but in general effective capacity demand for major hubs is expected to increase. De-routing to other airports in the metropolitan area is a possibility, but it is usually not what consumers want.

Two additional points suggest that congestions will remain and even deteriorate in the future:

- From a theoretical point of view, capacity of an airport should be increased, if the marginal benefit of an increase in capacity (measured by the consumer rent of the passengers using the new capacity) is larger than the marginal costs of the additional capacity. A capacity shortage at peak hours is thus well in line with an efficient capacity level of an airport [15].
- If an airport is dominated by a major hub airline it will only be able to gain a part of the benefit associated with the capacity expansion. This decreases the incentives for a commercial airport to increase capacity, potentially leading to an underinvestment [18]. Given the move to deregulate airports in Europe, this will also increase the mismatch between supply and demand for runway capacity at major airports.

Excess demand at selected airports (even beyond the congestion problem) will therefore be an increasing issue in the US and in Europe implying that there is an existing (unaccommodated) willingness to pay of the consumers for using special airports at peak hours.[8]

Literature tries to address this issue through peak-load pricing[9] (e.g. [4]; [6]) or slot trading (e.g. [5]; [16]; [24]) the essence of both approaches being a reduction of this excess demand through the price mechanisms. A different approach put forward in this paper is not to reduce demand, but to give airlines the technical possibilities to accommodate this excess demand with ESTOL capable aircraft which would allow using scarce infrastructure more efficiently. (How operation of such a system could look like will be described in paragraph 5.1.)

Potential customers for such an aircraft would be all those who are willing to pay for using the respective airport at peak hours: transfer passengers who use the airport as hub as well as time sensitive travellers (probably business) with a low price elasticity of demand. The latter might certainly also be served by a different airport in the area, but as long as these airports are no perfect substitutes, there is still an additional willingness to pay for using the (congested) airport. It should be noted that slots are highly complementary to each other for an airline, implying strong network externalities. To be able to serve a special airport at a special time might be much more valuable to an airline than the direct benefits to the passengers using that flight might indicate, e.g. by increasing possible aircraft utilisation. (For this argument see e.g. [2].)

Such a concept would probably have to bear a penalty due to higher energy consumption during take-off and landing and potentially during cruising (due to the heavier weight) as well. A basic prerequisite for such a concept to work is hence that the potential benefit to consumers (and thus the willingness to pay) is larger than the additional cost (which might be mitigated by a hybrid approach.[10])

The basic arguments can be visualised by FIG 1. The diagram shows demand D (marginal willingness to pay) and supply S (marginal costs) for travel services to a special airport at a special time of the day. Without any capacity restrictions airlines would offer X_0 flights to this destination at the price p_0. If there is a capacity constraint only X_c flights during a special time period are possible, allowing airlines to push the price of these services above

[5] This development will most certain be accompanied by a decrease in average aircraft size: Increasing airline competition will put additional pressure on the airlines to increase frequency of services and load factors. Both factors strongly favour the usage of smaller aircraft which intensifies capacity demand.

[6] See also for example [7]. Based on their analysis up to 60 airports in Europe (even accounting for new infrastructure investments) will be congested at peak hours. The top 20 airports will also be saturated 8 – 10 hours.

[7] 60-65% of all flights at the 10 biggest hub airports in the US have regional destinations up to a range of 600nm [30]; we found that 67% of the flights at Munich airport are in the range under 500nm.

[8] For Europe alone this might well add up to 3.7 million flights per year [7].

[9] Peak load pricing has been practiced in Heathrow and Gatwick since the 1970s in order to equalise peak and off-peak demand and to reduce flights with a low slot-productivity. This measure was successful to some extend, but still insufficient in order to cope with excess demand and congestion.

[10] As demonstrated in chapters 5.1 and 5.2 the HyLiner concepts combine the advantages of different technological or transport system characteristics.

marginal costs (p'). Accordingly, any additional flight will be very attractive for the airlines. Peak load pricing would increase airlines costs and therefore shift the supply curve upwards so that the rents are reaped by the airport (S'). However, if there is an aircraft type which allows serving more flights than illustrated by the capacity constraint, profitability depends on the additional costs airlines have to pay for operating such an aircraft. (The effective capacity limit is shifted to the right.) In FIG 1 this is represented by the supply curve S'' which lies above S. As long as S'' is below p' additional rents (represented by the shaded area) can be gained by the market players.[11]

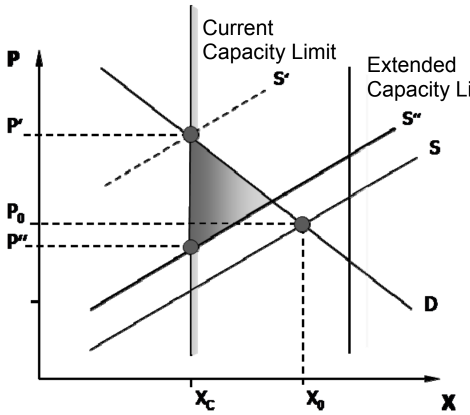

FIG 1. Simple model of the market for flights to and from congested airports.

However this might not be enough. Three other points have to be taken into account:

- As the additional costs are certainly private in nature, the benefits might well be external: if an airline operates such a system and reduces thereby congestion, all other flights operating at peak hours will benefit. It is therefore essential for such a concept to work that the benefits are private in nature as well. This certainly depends on the organisation of slot allocation and the pricing mechanism of the airport. A potential solution would be to allow airlines to use one slot to start more than one aircraft at the same time.
- There is a coordination problem involved for the airlines since they need two or even more aircraft to start (or land) at the same time.
- There are strong network externalities involved. The more aircraft of this type are in operation the greater is the benefit to the single user since he now has more options to use these specialised aircraft.

These arguments strongly favour the leading carrier at an airport for the usage of such a system: on the one hand the leading carrier operates several flights to and from the respective airport such that (as [3] already pointed out) it can internalise a big part of the otherwise external benefits and network externalities. On the other hand it is much easier to coordinate the necessary operations within one company or an airline network than between competitors.

When designing such an aircraft it has to be considered, that these aircraft will typically serve city pairs where only one airport is potentially congested. And congestion might well only occur at special hours of the day. This implies that such an aircraft needs to be flexible enough to be operated as a conventional aircraft (with conventional take off and landing (CTOL) procedures) without a significant penalty.

2.2.2.2. Development of the Transport Systems

Besides this air-transport specific problem of airport congestion, we would also like to draw attention to the future of the whole transport systems particularly in Europe. Other modes of transport are - on the one hand – necessary for air transportation, like the connection from and to the airport by car, train or coaches. On the other hand - they are direct competitors especially for the short to medium range travels. We know from previous experience, that air transport can lose considerable market share, when cities are connected by a high speed train connection. FIG 2 shows the development of future expected rail market share and therefore implicitly the loss of air transport market share.

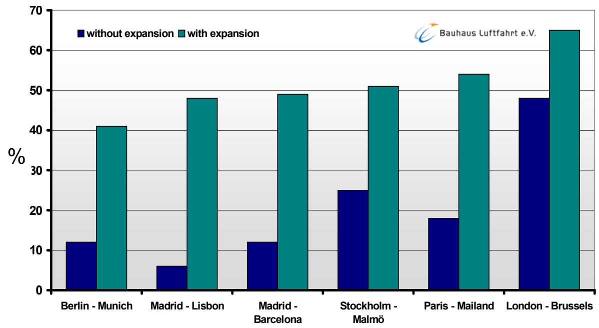

FIG 2. Rail transport market share 2020 with and without rail high speed network expansion [14].

Discussing the potential of regional air transportation therefore requires a discussion of the whole transport system. FIG 3 shows the current and forecasted European high speed network envisaged by the European Commission.

FIG 3. Current and forecasted European high speed network 2020 [27].

[11] This certainly depends on the underlying market structure and competition in this market. A monopolistic airline for example would have to take the price reduction for the intramarginal flights into account.

As the different transport systems compete for scarce public funds, the development of a high speed network partly comes at the expense of fewer investments in less densely populated areas. Moreover, the development of road infrastructure seems to have a high priority, particularly in the new member countries [25]. Due to high infrastructure costs[12] road and rail transport face similar congestion problems as air transport. This is illustrated by FIG 4 (dark areas indicate high levels of congestion.) [13]

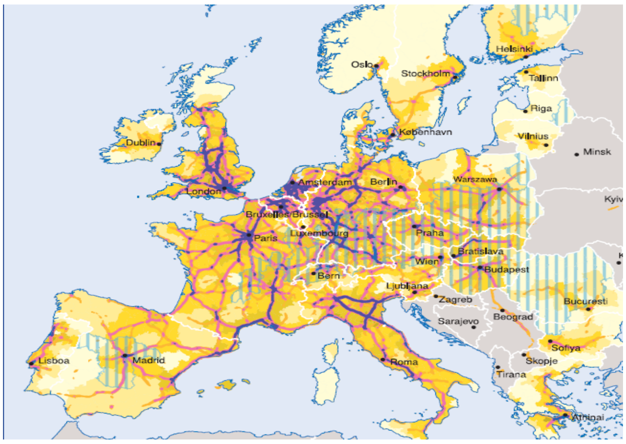

FIG 4. Congested Transport Corridors in Europe [9].

Against this background it is worthwhile recapitulating the consumer's mobility preferences. Consumers want to move from A to B. Which mode of transport they use is only of secondary importance [22]. Every mode of transport has its specific advantages and disadvantages.[14] The rail connection between two major cities is often unproblematic. This might indeed easily change if passengers want to travel between two cities which are not covered by the main high speed network. There are some changes - especially in Europe - to facilitate the connection between transport modes but these approaches concentrate on the connection of airports to the high speed rail network.

In this paper we want to suggest new possibilities of intermodal transport. It might be possible not to exchange passengers between the modes of transport but to exchange the different modes of transport, the respective propulsion units themselves. Such a concept would combine the advantages of city centre connections (of the rail system) with the speed and the low infrastructure cost of the air transport system *besides* the high speed network and *without* the annoying and time consuming personal transfers. Door to door times especially between less densely populated areas could thus be reduced substantially. Such a concept could additionally alleviate traffic concentration in the major agglomeration areas and congestion at major hubs. It would also require a VTOL technology to guarantee a safe exchange of the respective carrying system for the passenger cabin under a lower infrastructure requirement than conventional take off and landing (CTOL) concepts. A possible approach to such a transport system is introduced in paragraph 5.2. [15]

2.2.3. Unsustainable Growth in China

The most populous country is simultaneously among the fastest growing economies in the world: China. This combination of a large population and strong economic growth is not only a main driver for a very fast reduction in worldwide poverty; it also entails a couple of challenges and problems in particular for the traffic infrastructure.

Real per capita income in China has more than tripled in the past 15 years (from US$300 in 1990 to US$1000 in 2005) and will most probably continue to increase with remarkable high growth rates. This will certainly have a major impact on Chinese income distribution and consumption patterns. According to [29] about 360 million Chinese will have ascended to the global middle class by 2030[16]. This new purchasing power will especially increase the demand for mobility considerably. According to the Civil Aviation Administration of China (CAAC) the ratio of self-paying passengers in China has already exceeded 50 percent in 2005. In addition to this development, freight and business travel will increase at an even higher pace, reinforcing demand for (high end) city connections in the region. Total amount of passengers carried has risen so far from 30.4 million in 1990 to 138.3m in 2005 and is expected to rise up to 770 million in 2020.

Airport development in China by contrast, has been much slower than air traffic development. In 1978 only 81 airports were in use, none of which was big enough to handle a Boeing 737. In 1997 there were 141 airports, whereas 90 of them could handle a 737 and 14 were up to handle a 747. Since then only one additional airport (Guangzhou International) has been finished, while air traffic has doubled in the same time period (but several others have been extended) – and only four of them have the ability to handle air traffic under (almost) all weather conditions (ILS CAT II). This suggests that the enormous projected traffic growth in China will encounter similar capacity problems as Europe and the US are facing today,[17] but future extension will probably be more demand-oriented than in Europe, where many military airports have been converted into highly subsidised regional civil airports with low demand.

[12] According to [20] 1km of high-speed track has average costs of 6.5 million Euros.

[13] In the US high speed trains are much less of an option for politicians, given the huge dimensions of the US. However, it remains to be seen how the future developments of the oil price and the ecological discussion will influence the US rail transport system.

[14] Given the high preference for door to door transport, car transportation has a great advantage, which however comes at the cost of high fuel expenses, depreciation and potential congestions. Air transport offers the fastest connection at a roughly estimated travel distance of at least 600 km, but suffers from the relatively long periods spent on the trip to the airport, on check-in procedures and on security checks. (High speed) trains offer fast and stress-free city centre connections whereas the comfort of which strongly depends on the respective city pair.

[15] Such intermodal concepts will be much easier to handle and organise, if market access to the rail system and slots is facilitated. Such systems could than be operated by an airline or a rail company.

[16] The global middle class is defined as individuals earning an income falling between the per capita income of Brazil and the per capita income of Italy.

[17] India has actually a deficit in infrastructure development that is even more severe than in China. The Indian governmental budget deficit in relation to GDP is (with about 53 percent) more than twice as high as in China (see TAB 1). This exacerbates the problem, which is already now a decisive retarding element for the Indian economic development. Every transportation system that allows a better connection to and between major cities at affordable prices in spite of low infrastructure requirements will meet a large and increasing demand in this region.

A different transport system –the Chinese railway network- is currently underdeveloped with respect to length and quality. The total track length of about 75,000 km is put into perspective when related to total population and area, which gives 0.57 km per 10,000 people (worldwide ranking below 100) and 78 km per 10,000 m² (worldwide ranking below 60). However, the system will be extended by several high speed tracks in the coming decades. This network will connect several mega cities in the eastern coastal region, leaving a large fraction of the geographical region of China poorly connected. A transportation system with low infrastructure requirements that allows connecting such regions (with topographical hindrances for good road or railway connection) to the fast railway network is not available – yet. However, it has to be noted that despite the large geographical magnitude, the average travel distance per rail is only 800 km [21]. This number gives an impression of the range requirement for an aircraft operating in this region.

The strong economic growth is accompanied by increasing urbanisation, which puts additional pressure on the transport infrastructure within cities. The average duration for the trip from the city centre of a Chinese metropolis to the airport already takes now about 50 minutes.[18] This is a severe challenge for regional air transportation in China. The passenger has to spend a long time for the trip to the airport whereas the distance to be covered is not long enough to have a significant advantage against other modes of transport. This might well be another chance for a VTOL technology: high speed regional door to door services connecting city centres for time sensitive (business) travellers. Neither train nor a normal regional aircraft operating from the local airports will probably ever be able to match the door to door time of such a system. Given the necessary low infrastructure VTOL compatibility and the relatively short distances which do not require cruising speeds of above Mach 0.7, this seems to favour a propeller solution.

3. GENERAL DEMAND IMPLICATION FOR V/STOL TECHNOLOGIES

In brief one can resume the previous analysis by the following synthesis: the investigated regions face partly similar, but also quite different problems concerning their transport system. The strong growth of the market offers manufacturers and airlines new possibilities and new challenges. The ongoing trend of a reduction of aircraft types seems to be reversed as a market segmentation is presumable. Those manufacturers will gain the future which serve customer's preferences best.

With the growing volume of the air transportation market infrastructure is getting more and more congested and will reach capacity limits. We see a potential for V/STOL technology to address several of these challenges that occur in very different global regions. This technology strongly matches consumer's preferences for direct connections and provides independence from infrastructure requirements that might be crucial in the coming decades.

With respect to higher flexibility, better door to door times and higher passenger comfort the ongoing market liberalisation might allow free access to the required infrastructure for intermodal transport in a growing number of countries. This in turn sheds new light on the potential of intermodal transport, which requires VTOL capabilities. Capacity shortage at major hub airports might be alleviated by new ESTOL concepts, allowing a better utilization of existing capacities, without an enlargement of the airport's area.

Several programmes were already undertaken decades ago and again suspended. Hence an analysis of past V/STOL projects is indispensable for evaluating the potential and possible hazards of a reuptake of vertical flight.

4. EVALUATION OF FORMER AND RECENT APPROACHES TO V/STOL

To develop potential new solutions for the future, that satisfy the identified requirements, former and recent approaches of V/STOL concepts will be evaluated first. Although this paper shows some of the perspectives of V/STOL concepts in commercial aviation, not only some former civil V/STOL concepts will be analysed, but former and recent military V/STOL concepts and technologies will be discussed.

V/STOL has been of interest for about half a century. German and US V/STOL activities started in the mid 1950s. Many civil and military concepts were developed and some of them ground- or even flight-tested. Until now, only three of them (MDA/BAe Harrier, Yakovlev YAK 38 and Bell Boeing V-22 Osprey) have gone into service, a fourth - the Lockheed Martin JSF F-35B - will enter soon.

4.1. Former German V/STOL Activities

German V/STOL activities started with military applications such as the Do 31, VJ 101 and VAK 191 (for detailed information see [11]) driven by NATO's strategy of nuclear retaliation and runway independence. These concepts demonstrated feasibility in the 1960s and were all flight tested. After the change of NATO's strategy to flexible responses the German air force cancelled these programmes. To reuse the (sunken) investment out of these concepts a civil programme was launched in 1968. Several concepts were presented to the *Thalau Commission* in 1970. At that time it was argued that these concepts were able to

- receive a share in short range traffic volume,
- cover especially the business travel dominated ranges (of then 600 to 800 km),
- act as a passenger carrier to and from major airports (which provide the long range flights),
- connect cities with increased traffic volume by means of air transportation,
- offer seats for 80 to 100 passengers (economy class layout) and pressurized cabin for passenger comfort,

Benchmark was a Boeing 737–130 and direct passenger seat mile cost should not exceed 150% considering a 370 km distance (170nm). Cruise speed was supposed to be 740 km/h TAS (400 kts). Vertical take off and landings should be possible under cross winds up to 30 kts. Two legs of 315 km (170 nm) should be flyable without refuelling during mid mission landing. With respect to military operations the proposed V/STOL designs had to be highly flexible concerning all weather flying and

[18] To illustrate the pressure on the urban infrastructure: In Shenzhen for example about 500 new cars are bought every day. Bejing even has to bear the double amount of daily readmissions [26].

operation from areas with low or no infrastructure, like grass fields, aerodromes or even highways or streets [28].

The competitors proposed for the civil VTOL programme were

- the MBB Bo 140, a four-propeller tilt wing,
- the Dornier DO 231, fixed wing, based on the DO 31 with 12 lift engines and two cruise engines,
- the HFB 600 with 4 blade tip turbine driven lift-fans, 4 turbine driven lift/cruise fans and 4 control fans,
- VFW VC 180 with 10 lift engines and three cruise engines,
- VFW VC 500, a tandem tilt wing with 4 propellers and 8 turbines.

The V/STOL programme was cancelled in 1971 due to a lack of funding by the German air force because of budget shortcuts and decreasing interest of funding by Lufthansa. In addition the fuel crisis of the 1970's made it hard to justify the development of a V/STOL aircraft tending to have higher fuel consumption than conventional airplane designs. [12]

Looking at this approach from a today's perspective, the civil programme was certainly not well in line with the market needs at that time. First of all the overall market for air travel was certainly much too small. Secondly, although VTOL fulfils in a sense customers preference for short- and mid-range service, infrastructure was not scarce. Thirdly, the envisaged VTOL capability was certainly much too ambitious for this market. The penalty was more than the market was willing to pay.

As mentioned above the only civil driver for the VTOL activities in Germany was the intention to save expenditure after these concepts had been cancelled. Any arguments for civil applications have more or less been pushed forward to justify this. Therefore Lufthansa was not willing to bring in its own funds and lost interest for VTOL transport after the cancelling of public funds.

German activities stopped and are now triggered again by Bauhaus Luftfahrt.

4.2. US V/STOL Activities

In contrast to Germany, V/STOL activities in the US have been consistently continued from the 50s until today. Many different concepts have been developed, ground and flight tested, detailed analysis and documentation is available [13]. The majority of the concepts were military and government funded, and therefore not dependent on economic success.

The Harrier (a US and UK cooperation), a vectored thrust concept, has been hovering for almost half a century and has proved operability in several air forces.

The Lockheed Martin X-35B demonstrator won the Joint Strike Fighter (JSF) competition against the Boeing X-32 and will enter into service in the next years. It performed STOL, supersonic cruise and vertical landing in one flight. Short takeoff vertical landing (STOVL) capability is provided by a shaft driven lift fan behind the cockpit and a three bearing nozzle of the main engine.

The well known tilt rotor VTOL concept V-22 is a military tactical transporter and will enter into operational theatre in the end of 2007.

As discussed in detail before, today the situation has changed and civil V/STOL concepts are coming up again. The Bell-Agusta 609, the civil derivative of the V-22, is being certified. Institutions and companies like NASA, Boeing, Lockheed Martin and Northrop Grumman are coming up with 50-150 PAX ESTOL jet concepts [30].

4.3. Lessons learned from 60s V/STOL

Experience tells us that military driven mission requirements usually do not fit well in civil markets. This is especially valid for the V/STOL activities in Germany. However, the basic ideas followed with these technologies like direct door to door services without much infrastructure requirements certainly do match customer's preferences. But up to now the market has not been willing to pay the price for the additional development and operational costs. This might well be changing. The effects described above might give room for new V/STOL activities.

Following the already given international lines of experience, Bauhaus Luftfahrt has started to evaluate possible, promising V/STOL platforms combining several of the previously identified requirements; two of them are presented in the following section.Firstly, a turbofan driven fixed wing approach features the application of military V/STOL technology to a commercial design. This concept addresses the problem of infrastructure capacity shortage at major hubs. As mentioned above, such an aircraft should be flexible enough to operate under CTOL as well as under ESTOL conditions at a high cruise velocity. Therefore a fixed wing solution with turbofans seems to be the first choice.Secondly, a turboprop driven tilt wing design with application to short ranges features the ability of V/STOL capability and low infrastructure operability. Additionally it is possible to carry a passenger module compatible with high speed train platforms. This unique feature enables an unprecedented level of integration of future intermodal transportation systems and allows for highest transport flexibility.

5. POTENTIAL NEW V/STOL PLATFORMS

Bauhaus Luftfahrt pursues research on civil V/STOL aircraft concepts with the technology platform named “HyLiner” (short form of “Hybrid Airliner”). This project is understood to be a platform, where markets as well as technologies and research within this area can be bundled. "Hybrid” in this case refers to a combination of individual technologies and modes of operation that turn an expected penalty into a potential benefit. The mission (STOL and CTOL, intermodal transport), lift generation, flight dynamics, propulsion, steering and materials all belong to the hybrid concept. The goal – based on a collection of potential ideas and technologies – is the development of concepts, designs and technology demonstrators for ultra-quiet, low-emission short- and mid-range aircraft with VTOL and ESTOL capabilities.

5.1. HyLiner-R (ESTOL Regional Jet)

The „HyLiner-R“ is a potential solution for the addressed capacity problems of the major (hub) airports and can increase the capacity and flexibility of the hub airports by hybrid mission operation. Hybrid mission operation means the capability of operating in CTOL mode on conventional runways as well as in ESTOL mode on extremely short multi-slot runways. ESTOL capability is provided by low stall speed due to combination of dynamic and propulsive lift (hybrid lift generation). Low take off and landing speed makes 4-dimensional flight paths with low radiuses at acceptable passenger loads possible. When operating on CTOL runways the HyLiner-R integrates into the conventional take off and landing procedure.

5.1.1. Operation

FIG 5 shows a possible multi-slot operation at a generic three runway airport. One runway is operated by CTOL transports while the area of two main runways is converted into six extremely short runways without extending the total airport's area.

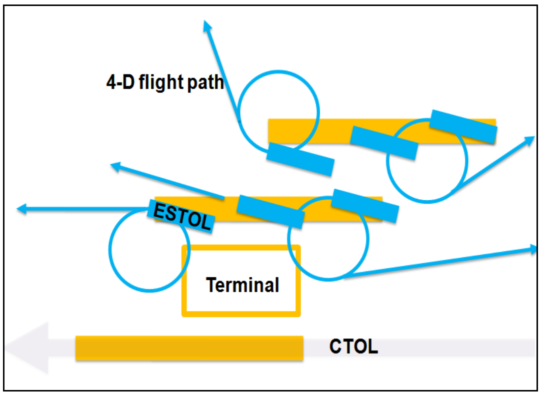

FIG 5. Possible multi-slot runways for generic three-runway airport.

Possible 4-dimensional spiral-flight paths have a radius of 600m (calculated for a bank angle of 24°, load factor 1.1 and a flight speed of 100 knots). It is aimed that most of the noise footprint remains over the airport-ground and does not affect close-by areas. The aircraft leaves the airport area after reaching a height that preserves residents from noise exposure. Hybrid mission operation increases airport's flexibility. Depending on demand the airport can decide whether to operate certain runways in CTOL or multi-slot ESTOL mode.

5.1.2. Fixed wing concepts

One approach to develop new concepts is the integration of different powered lift concepts into a conventional 50 seat regional jet. Lift fan technology is one option for V/STOL operation. It was first applied in the GE-Ryan XV-5A and eventually successfully operated in the F-35B. Fuselage mounted lift-fan concepts (FIG 6) are studied as well as fan in wing configurations (FIG 7).

FIG 6. Feasibility study: HyLiner-R multi-fan configuration (fans closed in cruise).

Due to high lift-fan area the needed power for additional lift at take off and landing is low and thereby the mass for the needed propulsion system. The HyLiner-R combines ESTOL capability with fast and efficient cruise by using hybrid propulsion. Power needed for additional lift at take off and landing is used for thrust generation in cruise flight.

Different concepts for power generation, transmission and supply are mechanical, pneumatic and electric, addressing different time horizons. Mechanical and pneumatic concepts are proved for high power in the megawatt class; electric concepts have not been applied for such dimensions, but are getting more and more interesting for long term applications as their weight is getting continuously lower. A one megawatt generator with a weight of 200kg is being developed by Innovative Power Solutions [19].

Pneumatic lift-fan propulsion system technologies were demonstrated among others by the GE-Ryan XV-5A and the German HFB 600 "Vertifan" in the 60s and 70s. The F-35B "Joint-Strike-Fighter" has a mechanical concept to shift power from the main engine to the lift-fan and increases its bypass ratio - and so the total force of the propulsion system - in this way.

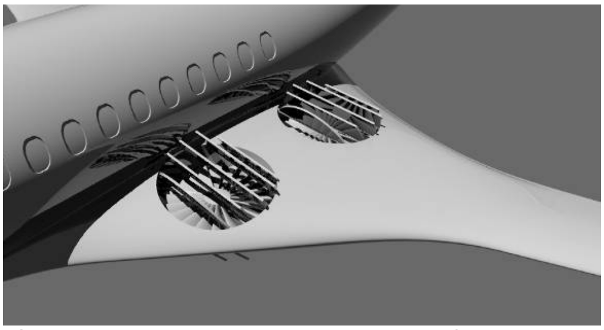

FIG 7. Feasibility study: HyLiner-R fan in wing configuration (fans open for take off and landing).

5.1.3. Enabling Technologies

As mentioned before, a combination of individual technologies to an ideal whole is a key goal in the HyLiner project. Required technologies and research activities serving this purpose are shown in TAB 2.

Technologies / research activities	Benefits
Development of a flexible design tool	Modeling of unconventional aircraft configurations
Thrust vectoring of high bypass engines	Additional lift and trim force
Advanced and/or new flight control systems	Control power for low speed flight
Variable bypass ratio power plants	High thrust at take off and landing combined with high cruise velocity
Hybrid propulsion system (utilisation of ESTOL power in cruise flight)	Reduces ESTOL penalties in cruise flight
Electric power plants and superconductivity	Flexible power shifting through the aircraft
Advanced analysis of lift-fan aerodynamics	Maximum lift for take off and landing
New structure design and materials	Optimal layout for special load cases

TAB 2. Technologies/research activities and their benefits.

5.2. HyLiner-V (VTOL)

The HyLiner-V represents a technology platform to address the demand of highly flexible transportation in the short range segment. In a first layout this approach incorporates inter-city transportation with low infrastructure demand. In a second step the HyLiner-V layout represents an interface between both ground and air based means of transportation. By equipping the HyLiner-V with a detachable passenger module, an unprecedented transportation system with greatest flexibility can be achieved. This feature gives the concept the ability to combine air transportation with ground based transportation systems like high speed rail (HSR) currently evolving in Europe and the Far East.

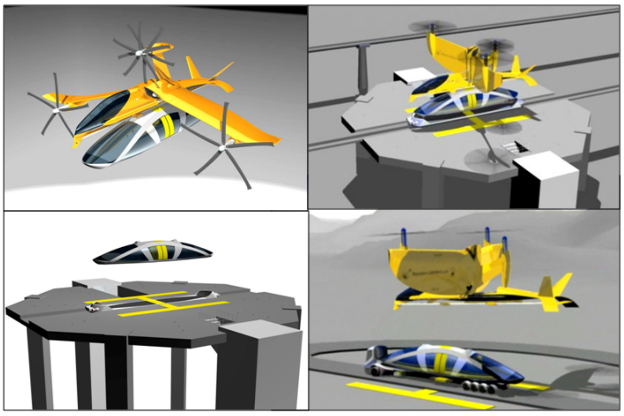

FIG 8. Artist view of the HyLiner-V technology platform featuring operational principles.

FIG 8 shows assorted artist views illustrating the HyLiner-V technology platform and its operation. Main features are the tilt wing design capable of transporting a HSR compatible passenger module. A free propeller propulsion system generates necessary thrust during VTOL and cruise condition.

This approach generates a new way of hybrid or intermodal travel enhancing overall transportation efficiency in the short range segment and accommodating passengers demand for door to door (city centre to city centre) travels without changing modes. With respect to these key features the HyLiner-V platform is able to achieve optimal performance, like

- high end door to door air transportation between cities with low need for additional infrastructure,
- intermodal flights from HSR stations with compatible passenger/freight compartments to connect surrounding less densely populated areas,
- intermodal connection flights between HSR stations with compatible passenger/freight compartments.

FIG 9 shows a generic mission profile for inter-city transportation. This type of mission capability especially addresses the corporate market needs of fast door to door travel and relieves surrounding airports from regional business travel. VTOL can be performed from fortified rooftops, floating vertiports, unused grass fields, etc.

FIG 10 shows two large cities connected via HSR. In this context the HyLiner-V performs as an extender of the HSR network, connecting low populated regions to the HSR system upgrading its transportation potential. The HyLiner-V is equipped with a passenger/freight module, compatible with both HSR and HyLiner-V fuselage for aerial transportation. In this configuration the HyLiner-V platform is additionally able to provide connection flights between HSR lines, where line routing would otherwise be highly expensive, as this is the case due to topographical hindrances.

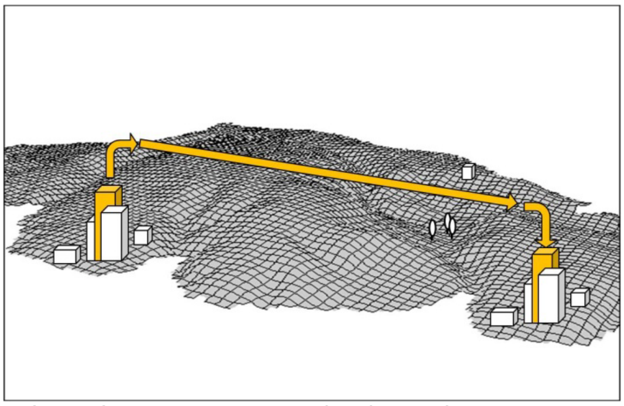

FIG 9. Generic mission profile for VTOL door to door inter city air transportation.

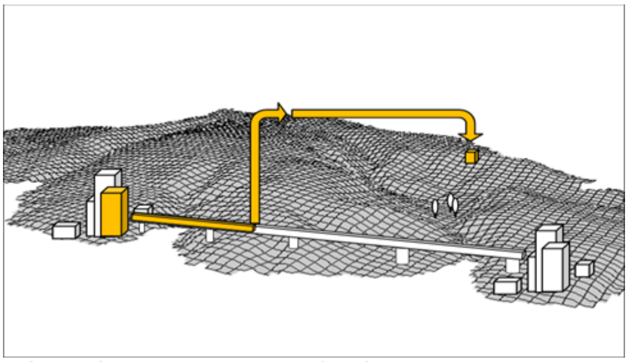

FIG 10. Generic mission profile for intermodal air-borne connection flight.

All of the presented cases require the HyLiner-V to be an extremely flexible platform with great interoperability potential. To form an adequate VTOL technology platform, the HyLiner-V concept features tiltwing technology in combination with free propeller driven propulsion system. This configuration allows for two flight modi: a hover mode and a cruise mode. VTOL is accomplished in the hover mode with wing in vertical position and lift generated by the propeller system. During hover phase the HyLiner-V is capable of lifting, carrying and releasing heavy loads. The hover mode enables the HyLiner-V to precisely land and position itself, even in difficult access areas (e.g. mountains, islands, urban canyons). To transport passengers or freight at high speed over longer distances, the HyLiner-V converts to cruise mode by tilting the wing in horizontal position, generating the necessary cruise lift by the wing and forward thrust by the propeller system. The propeller propulsion system used for hover and cruise condition has several advantages over a jet propulsion system. Especially with regard to required environmental compatibility the following characteristics of a propeller based propulsion are advantageous compared to a jet based propulsion [10]:

- higher efficiency in hover mode due to lower fuel consumption,

- VTOL capability from unfortified surfaces like grass fields due to low surface erosion,
- no danger of hot gas ingestion during hover mode,
- simple approach and landing procedures due to lower fuel consumption during hover phase,
- repeated deceleration of the air vehicle possible (likely in a missed approach) without having to restart auxiliary lifting devices,
- simple transition with wide (this means save) conversion corridor,
- balanced (hence economic) design due to equivalent power requirement during hover and maximum cruise speed mode,
- reduced mechanical complexity compared to a rotor design.

TECHNICAL DATA – INTERMODAL VTOL HyLiner-V Concept	
Concept	
Configuration	Tiltwing
Amount of passengers (PAX)	15 / 30 / 50
Length, fuselage	33ft / 66ft / 85ft (10m / 20 m / 26m)
Propulsion system	Turboshaft
Take off power	4000 / 8000 / 13500 kW
Weights	
Operating weight empty (OWE)	14 / 29 / 44 x 1000lb (6,2t / 13t / 20t)
Maximum take off weight (MTOW)	22 / 44 / 73 x 1000lb (10t / 20t / 33t)
Velocity / Range	
Maximum velocity	400 kts (740 km/h)
Maximum cruising velocity	325 kts (602 km/h)
Range, design point	650nm (1200 km)
Costs	
Base price	$ 13 - 50 million

TAB 3. Technical Data – Civil VTOL HyLiner-V.

The tilting wing configuration has the advantages compared to a fixed wing configuration of

- low propeller thrust losses in hover mode because of tilting wing surface,
- continuously thrust vectored V/STOL capability,
- high aerodynamic effectiveness of the wing during transition because of propwash wetted wing surface
- limited danger of stalling during landing because of favourable wing / propwash interaction,
- high cruise speed capability (up to 400 kts (750 km/h)).

First preliminary sizing approaches of the HyLiner-V platform included analysis based on statistics from historical data, knowledge from rotary and fixed wing experts as well as creative iterations enriched by industrial design approaches. As a first result the technical data presented in TAB 3 have been derived to fulfill the stated mission requirements.

To proof feasibility of the HyLiner-V VTOL technology platform, research and development is necessary in different technology fields to enhance operability, productivity and costumer appeal. For improved environmental friendly design, fuel consumption has to be reduced by addressing optimisation of engine efficiency, structural layout, improvement of aerodynamic efficiency during cruise flight and alternative fuel compatible engines. Customer's demand becoming more important, enhancement of comfort issues have to be addressed by further reducing cabin vibration level, which is of special concern to propeller designs. Vibration reduction also enhances endurance of pilots, improving operational safety level. Operational safety is especially important during low level operations (like hover phases) and require improved avionics to reduce pilot workload. Possible solutions include enhanced terrain awareness or routine task managing systems. Damage tolerant design or HUMS technology support safety issues from a structural point of view. Variable engine cycle and transmission speed technology have potential to increase cruising speeds (hence productivity) avoiding installation of oversized engines, optimised for either VTOL or cruise operation. The HyLiner-V technology platform and its operational capability consider the research progress of the stated technology fields which will be addressed by the industry as priority goals for the future. TAB 4 represents current VTOL research and development activities tackled by industry initiatives together with their goals focused for the next 40 years.

ENABLING TECHNOLOGIES – INTERMODAL VTOL HyLiner-V	
Configuration	
Optimisation of empty weight	-30%
Reduction of vibration	-10%
L/D comparable to turboprops	> 12
Improved damage tolerant design	
Propulsion	
Specific fuel consumption reduction	-25%
Improvement of power/weight	+80%
Reduction of life cycle costs	-30%
Variable cycle engine	emerging
Transmission	
Improvement of power/weight ratio	+40%
Reduction of noise	-15dB
Reduction of life cycle costs	-35%
Automatic detection of critical mechanical component failure	HUMS
Variable speed transmission	emerging
Avionics	
Enhanced terrain awareness	
Routine task managing system	
Real time weather navigation	
Highway-in-the-sky navigation	

TAB 4. Enabling Technologies for intermodal VTOL concept – HyLiner-V (based on [17]).

6. OUTLOOK

The analysis of transportation systems shows enormous market dynamics - the commercial aviation industry is changing rapidly. The current and future air transportation problems require new approaches. The presented V/STOL concepts offer contributions to the problems addressed in this paper. The VTOL concept HyLiner-V improves door to door times, integrates other transport modes into the air transportation system and therefore matches passenger's demand for transport service better. The ESTOL jet HyLiner-R increases airport capacity at peak hours through flexible runway operation without enlarging the airport area. Needed technologies for these concepts are identified and will be addressed by Bauhaus Luftfahrt in several co-operations.

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