Exploring the Prospect of Small Supersonic Airliners – A Business Case Study Based on the Aerion AS2 Jet

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We lay out the thesis that modern supersonic air transportation has the best chance of realization by commencing with small aircraft. A possible implementation path is described with reference to the Aerion AS2 supersonic business jet. Further, the paper entails an overview on the economic and operational challenges of supersonic airliners.

I. Introduction

MAN's never-ending quest for progress took a step backward when Concorde's airline service ceased in November of 2003. It had been a four-decades-long, highly controversial program that pioneered civil supersonic transportation. In spite of its undeniable technological success and in spite of being an aerospace icon even today – some will call it Europe's Apollo program –, it soon became evident that the undertaking was an economical failure. Only 14 aircraft were placed with British Airways and Air France, and the enormous development costs, shouldered by the British and French governments, were never fully recovered.[e]

Concorde stands as a monument to man's technological prowess as well as to what an economic disappointment an overly ambitious high-speed program can become. Considering today's ever more challenging global economic and regulatory environments, it appears probable that no nation or enterprise will anytime soon start a comparable prestige project without making sure that all stakeholders have a well-founded chance of profiting.

Previously, we assessed the possible market for supersonic business jets, testifying ambivalent prospects for contemporary development projects [1]. In another paper, we analyzed the global market of premium airline tickets with respect to future supersonic airliners, arguing that Concorde's passenger capacity would most probably be too large even for today's considerably grown air transportation market [2]. There, the idea was brought up that the most promising market for a supersonic aircraft could consist of the combined demand of both business jet customers and airlines.

This notion is developed further in the present work by assessing the airline perspective. We propose that smaller and moderately ambitious supersonic airliners have a better chance of realization. Moreover, we discuss the basic issues regarding the introduction of a small airliner by example of the Aerion AS2 supersonic business jet.

II. Rationale of aircraft program economics

Some will argue that larger supersonic aircraft have brighter prospects for economy of scale reasons: The bigger the aircraft, the less fuel it will consume per passenger, the less a ticket will cost, the more people will want to fly, and the more successful the aircraft is going to be. All these conclusions are generally valid, except for the latter, because it neglects the airlines' difficulties of filling big aircraft. That makes the original claim not just false, but also dangerous from an economic standpoint, because it will encourage the allocation of disproportional amounts of money and resources to projects that have a high risk of never returning a profit. The larger the stakes, the harsher is the fallout of failure: Concorde is blamed for having virtually dismantled the British civil aerospace industry by absorbing all government subsidies [3].

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[e] An encyclopedia of the Concorde project can be found at www.concordesst.com [retrieved April 2017].

A recent example of “(possibly) one step too far” is the A380 by Airbus. Planned as a bold move to trump Boeing’s 747 jumbo jet, to trade on ever-rising passenger numbers, and to make use of its two-deck economies of scale, the aircraft’s main purpose is to move passengers between large airline hubs. However, it turns out not to sell as well as originally envisioned, because fewer airlines and fewer hub pairs are proving able to provide the considerable passenger numbers required to fill the aircraft, and because smaller, fuel-efficient alternatives like the Boeing 787 enable airlines to open up new direct connections that previously had to be routed through hubs. Entering into service in 2007, only 317 A380s have been ordered to date (June 2017). Airbus itself reported a break-even on a per-aircraft basis only in 2015 [4], meaning that the bottom of the cash-flow curve had arrived and that losing money on each delivered aircraft had ceased. Granted, the A380 is the largest passenger aircraft ever built and therefore a technological marvel (as was Concorde); also reportedly, it is highly popular with passengers (as was Concorde). However, the manufacturer might never get a return on the investment – as was the case with Concorde.[f]

The very same logic applies to supersonic airliners: Sufficient destinations are needed where the aircraft can operate with a reasonable passenger load so that enough aircraft can be sold and so that both manufacturer and airlines can generate a profit.

Thus emerges the problem of what group of passengers can be expected to embrace supersonic airline service.

III. Airline passenger market basics

Since both development and operations of supersonic aircraft will be expensive because of their non-conventionality, higher technological requirements, and high fuel consumption, transportation will inevitably cost considerably more compared to their subsonic counterparts. For illustration, tickets on Concorde of British Airways were priced well above First Class in their Boeing 747 aircraft [5].

Coincidentally, ticket price happens to be the main decisive factor for most passengers, indicated by the fact that Economy Class dominates in all regular airlines. Further, there is a large price gap between Economy Class and both Business and First Class fares, the latter usually being a multiple of the former, which indicates the existence of two different markets that barely overlap. Therefore, only passengers routinely booking premium seats can be held able and willing to regularly afford supersonic airline service due to the necessity of high ticket prices. There are numerous travel reports by passengers flying on Concorde for the experience of a lifetime; however, no reasonable business model ought to rest on their hardly predictable occurrence. It also appears plausible that previously untapped demand will be stimulated simply by the novel offering, so that passengers who earlier had not deemed it worthwhile to fly at all will decide for a supersonic journey. Yet, their numbers can hardly be foreseen.

The two distinct reasons for seeking supersonic transportation are: saving time and vying for prestige. Since the latter’s importance can hardly be quantified (whereas it probably plays a significant role), we focus on the former. Passengers can best realize time savings – and justify purchasing an expensive ticket – on flight routings of greatest directness. This means that supersonic service will be most preferred by passengers not requiring (subsonic) connecting flights or layovers. Certainly, some will book supersonic regardless. Due to the compromised time savings however, those will probably not pose the core of the market and should not be counted on initially.

Further, supersonic airline cabins are usually designed for outfitting with regular, non-berthing seats simply because passengers will spend less time in them. This means that premium passengers who are used to fully reclining seats will have to lower their sights on seat comfort. The longer the supersonic flight takes, the fewer passengers will accept that trade, and past a certain duration (that we estimate to be between four and six hours for most passengers), their approval will decline sharply.

Thus, we suggest that the main customer group for supersonic airlines will be premium passengers on non-stop connections.

To determine an appropriate aircraft size in terms of passenger seats, two aspects are relevant on the passenger market side. First is the level of demand in terms of passenger numbers, which we address in the following chapter. Second is the price elasticity of demand. According to a meta-study [6], leisure passengers exhibit a rather price elastic demand, which means that a change in price corresponds to an inversely disproportional change in demand. In contrast, business passengers have a price inelastic demand, which means that a change in price leads to a smaller inverse change in demand.

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[f] Coincidentally, both Concorde and the Airbus A380 keep generating considerable publicity. This can be argued to have a positive effect both for the manufacturer, as it exudes prestige, as well as on the whole aerospace industry, as it serves as an inspiring and motivating icon. However, in light of today’s ever more competitive economic environment, there can be little doubt that a solid business case will be required.

The price inelastic demand of business travelers has twofold consequences for supersonic transport services. On the one hand, airlines can set high prices for a good product including, e.g., comfortable seating, lush on-board-service, convenient schedules, connectivity, and travel speed in particular. On the other hand, price inelastic demand also means that the positive effect of lower ticket prices on passenger numbers will be limited, at least unless we enter price levels where leisure passengers get on board.

Gillen, Morris, and Stewart [7] found price elasticities of demand for business passengers between -0.3 and -1.1, with the value of -0.3 for international long-haul business travel. Taking this figure as a basis for a relevant market point: if one considered building a bigger supersonic aircraft with more seats and lower unit cost, then 1% lower unit cost and 1 % lower ticket prices would attract only 0.3% more passengers to fill the bigger aircraft. Supposing a flat price for all passengers, one would be left with less revenue than before, whereas trip costs would rise coincidentally.

Granted, price discrimination is well established in the airline industry by means of Revenue Management. Therefore, one can assume to capture a higher share of consumer surplus by employing individual prices. Nevertheless, it remains far from clear whether one ends up with higher overall revenue by selling more seats in a price inelastic market.

All said, we conclude that it is doubly dangerous to pursue bigger supersonic aircraft: first, due to the improbability of considerably higher revenue, and second, due to the certainty of higher total cost.

IV. Focus on possible airline networks

Conventional airliner manufacturing programs require sales in the hundreds to turn profitable. Prerequisite for launching such programs are orders by reliable airlines (or aircraft lessors, for that matter) who usually purchase whole fleets to benefit both from quantity discounts and from operational economies of scale. Further, supersonic fleets will work most efficiently in dedicated branches with their own administration, personnel, and maintenance facilities because of their uniqueness and because of their initially separate airline network. In consequence, we suggest that the first supersonic airliners will probably be operated by major carriers in distinct entities and on separate flight plans.

With this in mind, the passenger market is assessed in a similar way to our preceding study [2], using more recent data from 2015: Global sales numbers of premium airline tickets are collected from a commercial database[g] which are then consolidated to comprise the journeys' origin and destination cities as well as passenger numbers, average fares, and average lengths of stay (*LOS*). Trend curves of yield (i.e. fare divided by distance) and length of stay are calculated over great circle distance[h], and the respective city-pair-specific trend deviations $\Delta Yield$ and ΔLOS are added to the list. With the help of interregional market growth figures from the Boeing Current Market Outlook 2016[i], the passenger numbers are then extrapolated to a future point in time when a supersonic airline could be fully operative, for which we choose the year 2030.

Hereafter, we deviate from our previous study that aimed to estimate the total market for supersonic airliners of arbitrary size. Instead, we look at possible single airline applications for one specific aircraft design, assuming that sustainable airline businesses will need to meet the economic conditions described above.

Airlines usually have bases where their networks originate from and where their maintenance facilities are located. Thus, passenger numbers of specific cities are examined to find possible airline bases. Additionally taking into account their aptitude for supersonic flight routing (see Chapter VI below), the following metropolises were found promising: London, New York City, Dubai, Hong Kong, Singapore, Paris, Tokyo, Sydney, Frankfurt, Sao Paulo, Miami, and Washington, D.C.. For these cities, lists of prospective destinations were compiled. (See Table 1 as an example for London).

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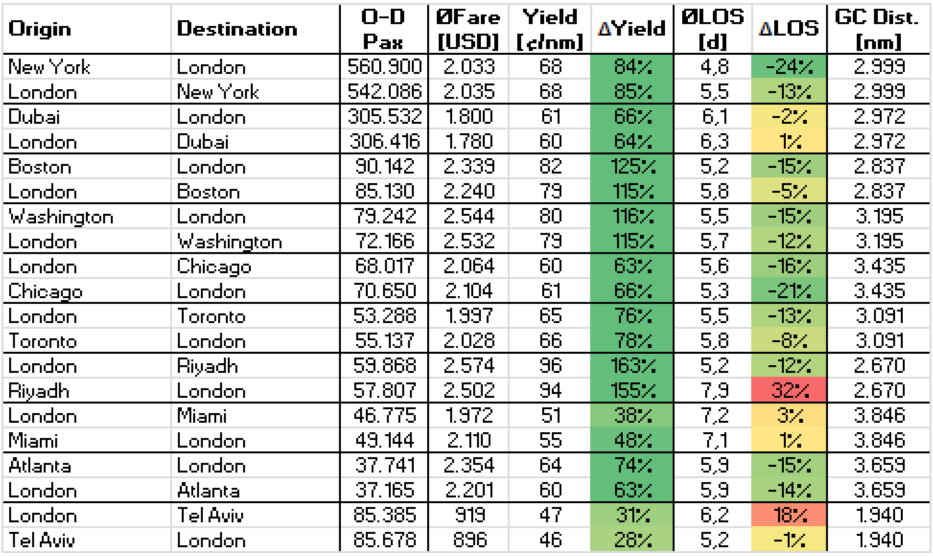
[g] Available online at www.sabreairlinesolutions.com/home/software_solutions/airports/ [retrieved March 2017].

[h] The trend curves show that for increasing distances, yield slowly declines and length of stay slowly increases. However, city-pair-specific figures exhibit considerable dispersion. High yield and short stay are considered conducive for supersonic transportation.

[i] Available online at www.boeing.com/commercial/market/ [retrieved March 2017].



Origin	Destination	O-D Pax	ØFare [USD]	Yield [¢/nm]	ΔYield	ØLOS [d]	ΔLOS	GC Dist. [nm]
New York	London	560.900	2.033	68	84%	4,8	-24%	2.999
London	New York	542.086	2.035	68	85%	5,5	-13%	2.999
Dubai	London	305.532	1.800	61	66%	6,1	-2%	2.972
London	Dubai	306.416	1.780	60	64%	6,3	1%	2.972
Boston	London	90.142	2.339	82	125%	5,2	-15%	2.837
London	Boston	85.130	2.240	79	115%	5,8	-5%	2.837
Washington	London	79.242	2.544	80	116%	5,5	-15%	3.195
London	Washington	72.166	2.532	79	115%	5,7	-12%	3.195
London	Chicago	68.017	2.064	60	63%	5,6	-16%	3.435
Chicago	London	70.650	2.104	61	66%	5,3	-21%	3.435
London	Toronto	53.288	1.997	65	76%	5,5	-13%	3.091
Toronto	London	55.137	2.028	66	78%	5,8	-8%	3.091
London	Riyadh	59.868	2.574	96	163%	5,2	-12%	2.670
Riyadh	London	57.807	2.502	94	155%	7,9	32%	2.670
London	Miami	46.775	1.972	51	38%	7,2	3%	3.846
Miami	London	49.144	2.110	55	48%	7,1	1%	3.846
Atlanta	London	37.741	2.354	64	74%	5,9	-15%	3.659
London	Atlanta	37.165	2.201	60	63%	5,9	-14%	3.659
London	Tel Aviv	85.385	919	47	31%	6,2	18%	1.940
Tel Aviv	London	85.678	896	46	28%	5,2	-1%	1.940

Table 1. Top ten destinations from London regarding premium passenger numbers, 2030 (2015 fares).
(Destinations suitable for reasonable non-stop overwater routing only. *O-D Pax*: origin-destination passengers; *ØFare*: avg. ticket fare, U.S. Dollars, excl. fees & taxes; *Yield*: revenue per nautical mile, U.S. Cents; *ΔYield*: deviation from yield trend curve; *ØLOS*: avg. length of stay, days; *ΔLOS*: deviation from length of stay trend curve; *GC Dist.*: great circle distance, naut. mi.. Color shades indicate favorability: Green is favorable, yellow is neutral, red is unfavorable.)

V. The Aerion AS2 supersonic business jet

We introduce, as a candidate example of a supersonic airliner, the Aerion AS2[j]. Its technical specifications and its exterior design are illustrated in Figure 1. Although it is being marketed as a supersonic business jet, i.e. a private aircraft, it closely fits the design and performance requirements for a supersonic airliner as outlined above and in the following sections. In particular, the AS2 cabin is designed for up to 9 passengers plus baggage and attendant(s) in accordance with highest levels of business aircraft luxury and functionality, but could be reconfigured to accommodate up to 19 passengers and baggage in levels of seating comfort equal or better than airline premium Economy Class, as shown in Figure 2.

<u>AS2 Performance Objectives</u>
Max. operating speed: M 1.5
No boom cruise: M 1.1-1.2
Max. IFR range
M 1.4: 4,750 nm/8797 km
M .95: 5,300 nm/9816 km
BFL at ISA, SL: 7,500 ft/2,286 m
Approach speed: 135 kts (typ.)
<u>Weights</u>
MTOW: 121,000 lb/54,884 kg
BOW: 57,801 lb/26,218 kg
Max. fuel: 62,000 lb/28,122 kg
<u>Interior dimensions</u>
Max. height: 6 ft 2 in/1.9 m
(flat floor)
Max. width: 7 ft 6 in/2.2 m
Cabin length: 30 ft/9.1 m
(cockpit divider to bulkhead)

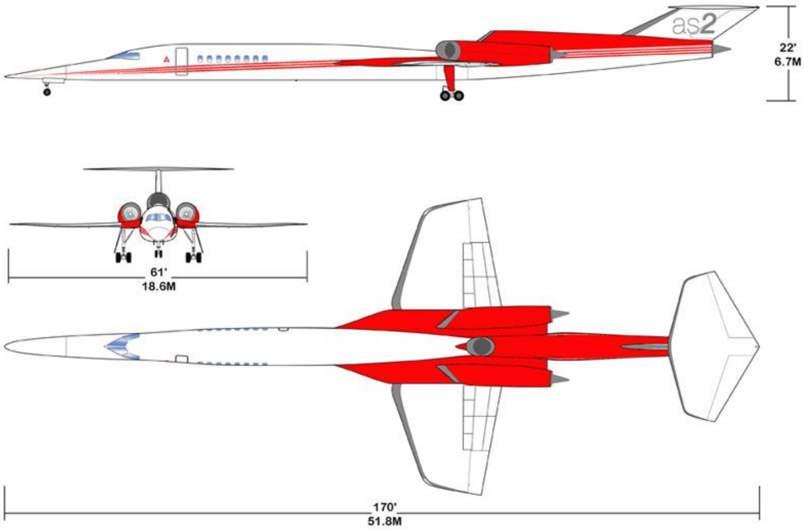


Figure 1. The Aerion AS2 Business Jet (courtesy Aerion Corp.)

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[j] For more information, visit www.aerionsupersonic.com [retrieved April 2017].

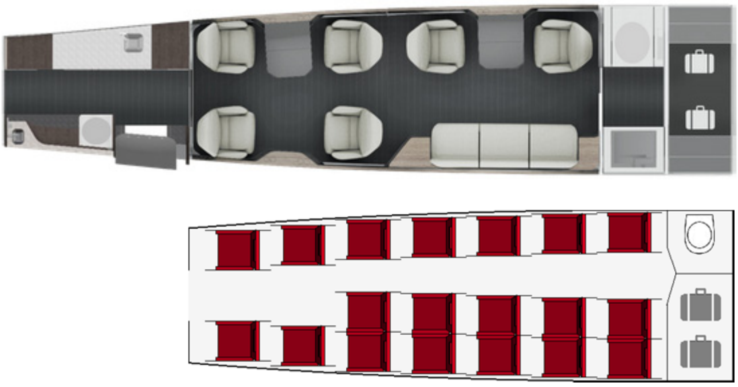

Figure 2. AS2 cabin configurations: private (top, courtesy Aerion Corp.) and airline (bottom) usage

The AS2 range target is 4,750 nm at Mach 1.4 and 5,300 nm at Mach .95, with a balanced field length of 7,500 ft at sea level ISA conditions at its gross weight of 121,000 lb. These specifications could be slightly different for a commercial airliner version, but not enough to affect the results presented here, since they are very consistent with the operational assumptions of the present analysis. In particular, the increased passenger and baggage weight would reduce the range target to about 4,500 nm, with IFR reserves.

The AS2 will comply with airport community noise regulations applicable to civil supersonic aircraft, which are under development at present, and are expected to be based on the rules for subsonic aircraft defined in FAA Part 36, Stage 4, and ICAO Chapter 14. Although the AS2 sonic boom will not be even remotely as severe as Concorde, it is not a "low boom" design. Its flight management system will enable flight at "Mach cutoff" speed slightly above Mach 1.1, where no boom reaches the surface [8]. However as explained below, operations at unrestricted supersonic speeds are assumed only over water or certain unpopulated areas, and otherwise the speed is restricted to Mach 0.95.

The market for supersonic business jets has been studied by numerous entities over past two decades, with the consistent result that an initial model would sell 300 to 500 units over its product cycle of 10 to 15 years. The inflation-adjusted price would range from about 100 to 130 million in 2016 USD, depending on the aircraft size and performance. As will be seen, the near term market for an airliner is substantially fewer units, so the advantage of adapting a business jet to the airliner role is the much larger total market to amortize the development costs and minimize the acquisition cost.

VI. Sonic-boom-compliant routes and missions

Supersonic overland flight was banned by most countries when the loudness of Concorde's sonic boom became public in the early 1970s. Since then, extensive research has been dedicated to understanding and abating sonic boom noise. NASA [9, 10] and JAXA [11] are presently designing and deploying "low-boom" demonstrator aircraft that are shaped to aerodynamically scatter the compression shocks so that they are perceived in a less disturbing manner when hitting the ground. As yet however, there are no commonly approved solutions for at least two grave issues: boom amplification during supersonic acceleration [12, 13] and increased annoyance indoors due to boom-induced rattle [14].[k] Therefore, public acceptance of supersonic overland flight (except for Mach cutoff) remains doubtful for at least the mid-term.

A straightforward solution to the sonic boom problem is rerouting flights around land masses and staying subsonic while over land, as has been done with Concorde. We previously determined that there are reasonable flight detours over seas and oceans for the majority of city pairs, still allowing for considerable time savings versus subsonic great circle flight [17]. In the future, bans might get lifted locally by employing supersonic corridors over uninhabited areas like Northern Canada, Greenland, or the Arab Desert.

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[k] Additionally, low-boom aircraft are known to trade aerodynamic efficiency for a lower boom (the so-called 'low boom, high drag paradox' [15, 16]). Whereas this harms economically, it also exacerbates a particularly weak point for future political debates: Low-boom aircraft are prone to condemnation for polluting the environment *even more* to enable booming the general public for the exclusive benefit of the upper class.

For the present study, it is assumed that overland bans will remain in effect and that supersonic airliners will have to take detours to realize optimum time savings. Flight routes between the metropolises introduced above and their respective destinations are designed accordingly.

This step effectively eliminates several possible bases from the assessment. For Los Angeles and San Francisco, all trans-pacific destinations are too remote for non-stop service with the AS2, and the other top destinations, mostly U.S., require long or even exclusive overland flight and considerable detours, respectively. New Delhi, Moscow, and Chicago are located far inland so that every supersonic mission would be compromised from the start. Johannesburg is remote from the most interesting destinations. Other cities are impaired by a mix of inadequate demand, low yields, and suboptimum locations.

Three sets of flight times are calculated for comparison purposes, all analogous to the methodology detailed in [17]: great-circle missions of a Mach 0.85 aircraft, AS2 all-supersonic great circle missions, and AS2 rerouted missions (also calculating mission fuels).

Figure 3 displays possible flight routes originating from London.

Figure 3. Supersonic non-stop flight routes from London [drawn in Google Earth[l]].

VII. Basic airline drafting

A flight destination's quality for the given purpose is assumed to be mainly governed by three factors:

- Average ticket yield – the higher, the better, since supersonic flight is expensive and therefore more competitive on higher-yielding destinations. A destination's deviation from the global yield trend is expressed in $\Delta Yield$ (see Chapter IV).
- Average length of stay – the shorter, the better, because long stays negate the need for quick transfers. A destination's deviation from the global length of stay trend is expressed in ΔLOS (see Chapter IV).
- Time efficiency of supersonic flight. This is expressed through the factor $\eta_{routing}$ that linearly correlates the subsonic great-circle, rerouted, and supersonic great-circle mission times T_{sub}, $T_{rerouted}$, and T_{super} (coincidentally illustrating flight routing quality)[m]:

$$\eta_{routing} = \frac{T_{sub} - T_{rerouted}}{T_{sub} - T_{super}} \tag{1}$$

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[l] The Google Earth application is available on www.google.com/earth [retrieved April 2017].

[m] With $T_{rerouted}$ nearing T_{sub}, $\eta_{routing}$ approximates 0. With $T_{rerouted}$ nearing T_{super}, $\eta_{routing}$ approximates 1.

The factors are combined to appraise a figure of merit *FOM* that proportionately expresses a flight destination's inherent (passenger-number-neglecting) potential for supersonic airline service:

$$FOM = (1 + \Delta Yield) \cdot (1 - \Delta LOS) \cdot \eta_{routing} \tag{2}$$

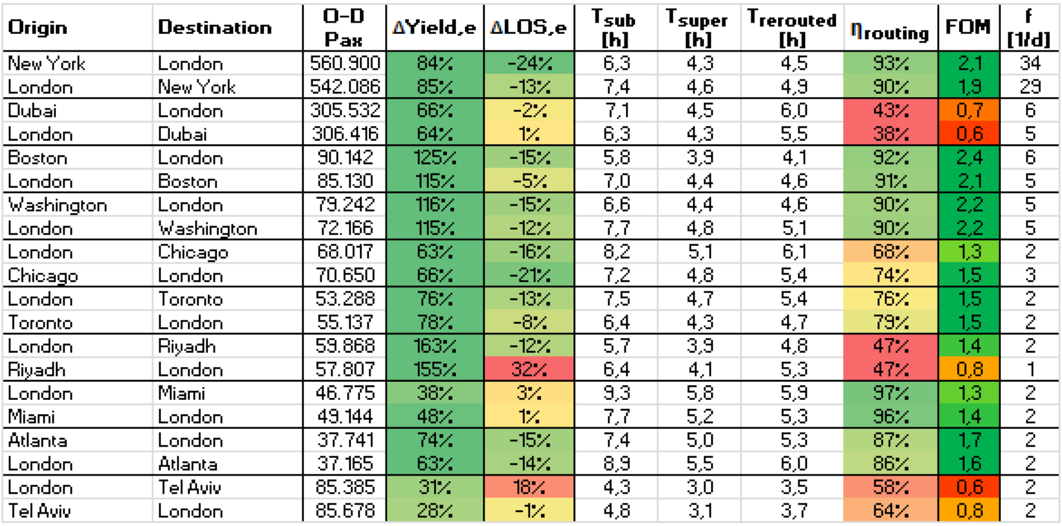
The basic market share parameter ms_0 is introduced to allow for sizing the market as a whole based on arbitrary opinions regarding competitiveness and market penetration of the given supersonic airline proposition. The final market share on specific city pairs ensues from the arithmetic product of ms_0 and *FOM*. We consider particularly high market shares, i.e. 50 % or above, unrealistic due to:

- the design-inherent reduction of seat comfort in supersonic airline cabins,
- comparatively moderate time gains due to regulatory and technological constraints (see Table 2 below),
- necessarily high ticket prices (see Chapter VIII below),
- expectable countermeasures by competing airlines, e.g. ticket discounting and political lobbying, in case of noticeable market disruption,
- a probable tightening of regulations if lavish and environmentally detrimental supersonic flight escalates.

Introducing *FOM* as a modulator of market share, the possible daily supersonic flight frequency *f* for a city pair *i* is calculated by[n]:

$$f_i = \frac{n_{pax,i} \cdot ms_0 \cdot FOM_i}{n_{seats} \cdot slf \cdot 365} \tag{3}$$

In supersonic service, the dominating passenger segment will probably be time-sensitive business travelers who appreciate multiple flight times to choose from. Also in theory, there is a nonlinear correlation between flight frequency and market share (the so-called S curve [18]) that causes the frequency leader to capture a disproportionate percentage of passengers. Therefore, supersonic service frequencies should be as high as possible and preferably come close to the subsonic ones, whereas the latter is particularly difficult for the busy destinations at hand[o]. At the same time, high frequencies are facilitated by the fact that the proposed AS2 airliner merely has 19 seats.



Origin	Destination	O-D Pax	ΔYield,e	ΔLOS,e	T_{sub} [h]	T_{super} [h]	$T_{rerouted}$ [h]	$\eta_{routing}$	FOM	f [1/d]
New York	London	560.900	84%	-24%	6,3	4,3	4,5	93%	2,1	34
London	New York	542.086	85%	-13%	7,4	4,6	4,9	90%	1,9	29
Dubai	London	305.532	66%	-2%	7,1	4,5	6,0	43%	0,7	6
London	Dubai	306.416	64%	1%	6,3	4,3	5,5	38%	0,6	5
Boston	London	90.142	125%	-15%	5,8	3,9	4,1	92%	2,4	6
London	Boston	85.130	115%	-5%	7,0	4,4	4,6	91%	2,1	5
Washington	London	79.242	116%	-15%	6,6	4,4	4,6	90%	2,2	5
London	Washington	72.166	115%	-12%	7,7	4,8	5,1	90%	2,2	5
London	Chicago	68.017	63%	-16%	8,2	5,1	6,1	68%	1,3	2
Chicago	London	70.650	66%	-21%	7,2	4,8	5,4	74%	1,5	3
London	Toronto	53.288	76%	-13%	7,5	4,7	5,4	76%	1,5	2
Toronto	London	55.137	78%	-8%	6,4	4,3	4,7	79%	1,5	2
London	Riyadh	59.868	163%	-12%	5,7	3,9	4,8	47%	1,4	2
Riyadh	London	57.807	155%	32%	6,4	4,1	5,3	47%	0,8	1
London	Miami	46.775	38%	3%	9,3	5,8	5,9	97%	1,3	2
Miami	London	49.144	48%	1%	7,7	5,2	5,3	96%	1,4	2
Atlanta	London	37.741	74%	-15%	7,4	5,0	5,3	87%	1,7	2
London	Atlanta	37.165	63%	-14%	8,9	5,5	6,0	86%	1,6	2
London	Tel Aviv	85.385	31%	18%	4,3	3,0	3,5	58%	0,6	2
Tel Aviv	London	85.678	28%	-1%	4,8	3,1	3,7	64%	0,8	2

Table 2. Top ten London destinations, 2030: possible service frequencies for ms_0 = 15 %, *slf* = 75 %.
(T_{sub}: great circle block time, Mach .85 airliner; T_{super}: great circle supersonic block time, AS2; $T_{rerouted}$: rerouted supersonic block time, AS2; $\eta_{routing}$: supersonic routing efficiency; *FOM*: figure of merit; *f*: flight frequency. Color shades indicate favorability: Green is favorable, yellow is neutral, red is unfavorable.)

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[n] n_{Pax}: yearly number of premium passengers; n_{Seats}: number of passenger seats on the aircraft; *slf*: in-service average seat load factor.

[o] For instance, non-stop daily flight frequencies from London in the (less busy) winter flight plans of 2015-2016 are 25-29 to New York City, 14-15 to Dubai, 5-7 to Washington, 4-5 to Mumbai, and 4-6 to Boston.

As an example, Table 2 shows resulting flight frequencies for London destinations, assuming a basic market share ms_0 of 15 % and an average seat load factor *slf* of 75 %. A destination is assumed to qualify for supersonic service if it allows for a certain minimum flight frequency f_{min}. Assuming f_{min} = 2/d as well as an average daily aircraft utilization of 10 hours[p], the strongest five resulting airline bases with their destinations are detailed in Table 3. Those could host a global fleet of 142 AS2 aircraft under the given conditions.[q]

Base	New York												London					
Destin.	London	Paris	Miami	Frankfurt	Zurich	West Palm Beach	Amsterdam	Mexico City	Fort Lauderdale	Orlando	Milan	Geneva	New York	Dubai	Boston	Washington	Chicago	Toronto
f [1/d]	16	9	4	3	3	3	2	2	2	2	2	2	16	6	6	5	3	2
ms [%]	15	31	14	25	28	22	32	18	16	14	15	32	15	10	33	33	21	23
Fleet	43												37					

Base	Singapore											Tokyo						Hong Kong				
Destin.	Hong Kong	Shanghai	Tokyo	Mumbai	Taipei	Seoul	Manila	Beijing	Sydney	Delhi	Dubai	Taipei	Hong Kong	Shanghai	Singapore	Okinawa	Bangkok	Singapore	Tokyo	Seoul	Jakarta	Kuala Lumpur
f [1/d]	8	8	4	4	4	3	3	3	2	2	2	12	5	8	4	7	4	8	5	5	3	2
ms [%]	12	18	9	20	12	17	20	14	10	15	18	17	10	15	9	11	14	12	10	13	17	19
Fleet	31											19						12				

Table 3. Prospective supersonic airlines with destinations, flight frequencies, market shares, and fleets (2030).
(Shaded fields indicate city pairs serviced by two complementing airlines. *f*: daily flight frequency; *ms*: passenger market share.)

When the basic market share ms_0 is varied to 10% and 25 % and the minimum daily frequency *f* is varied to one and three, the resulting global fleets comprise 63 to 314 airplanes (see Table 4).

Due to the introduction of *FOM*, the resulting market shares differ from the basic ms_0. A measure of global market penetration over all served destinations *i* and quasi the overall result of multiplying ms_0 by *FOM,* the frequency-weighted mean market share ms_{mfw} is calculated as follows:

$$ms_{mfw} = \frac{\sum ms_i \cdot f_i}{\sum f_i} \tag{3}$$

Respective to the basic market shares ms_0 of 10/15/25 %, ms_{mfw} results to 15/22/36 % (see Table 4). At least the latter percentage would have to be rated market-disruptive, even more so on certain particularly favorable city pairs where more than 50 % of premium passengers would then switch to supersonic (e.g. London – Boston; see ms_{max}).

ms_0	**Global AS2 airliner fleets**			ms_{mfw}	ms_{max}
	f_{min} = 1/d	f_{min} = 2/d	f_{min} = 3/d		
10%	**107**	**73**	**63**	15%	23%
15%	**175**	**142**	**110**	22%	35%
25%	**314**	**274**	**242**	37%	58%

Table 4. Global fleets and passenger market shares for given basic market shares.
ms_0: basic market share; f_{min}: minimum daily flight frequency; ms_{mfw}: frequency-weighted mean market share;
ms_{max}: maximum occurring market share

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[p] The average daily aircraft utilization of the large carriers Delta Airlines, American Airlines, and United Airlines was 10.14 hours in 2015 and was between 9.32 and 10.65 hours from 1995 to 2015 (the latter figures including the absorbed Continental Airlines, Northwest Airlines, US Airways, and America West Airlines).
See http://web.mit.edu/airlinedata/www/Aircraft&Related.html [retrieved April 2017].

[q] The next biggest airlines would have been based in Dubai and Paris with fleets of six and five aircraft, respectively. In order to maintain reasonable fleet sizes, we decided to make a cut and to assign all possible shared frequencies and the required flights to the respective bigger competition. When taking into account all remaining bases, the global fleet would merely consist of 149 aircraft instead of 142.

VIII. Estimation of operating cost and of ticket prices

High-speed air transportation is inherently expensive. As velocity increases, so does aerodynamic drag and consequently, fuel burn, the latter being a major cost factor in airline service. Recent supersonic airliner design studies by Boeing [19] and Lockheed Martin [20], aimed at an entry into service in the 2030-2035 period and already comprising future technologies, promise fuel efficiencies of 4.5[r] and 3.64 seat-nm per pound of fuel on their design missions, respectively, equivalent to 6.81[r] and 8.42 L/seat/(100 km). Contemporary long-haul aircraft feature fuel efficiencies around 3 L/seat/(100 km) [s] [21], whereby this figure can be expected to drop even more over the next two decades due to the use of higher-bypass engines, high-aspect-ratio wings, and lighter structural materials.

Conventional cost models were found inappropriate for supersonic airliners because they are usually based on empirical data of subsonic aircraft and because most of them neglect single cost items. For that reason, a new parametric cost scheme for calculating direct operating cost (DOC) was developed. It includes expenses of fuel, engine and aircraft maintenance, navigation, airport operations, passenger service, crew, and ownership. Some items are determined empirically, some analytically, some have to be best-guessed.

Figure 4 shows the resulting DOC of an airline mission that connects the London-Luton and New York-JFK airports using the Aerion AS2, whereby supposedly conservative assumptions (i.e., on the high side) were made. Apparently, the most important items are capital cost (depreciation + insurance + interest), fuel, and engine maintenance. Mission cost per seat is about $2,272, cost per available seat (nautical) mile (CASM) is ¢75[t].

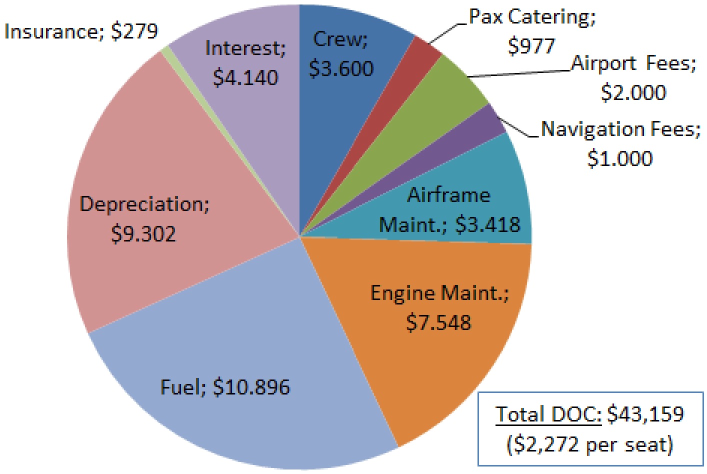

Figure 4. Direct operating cost of a London (LTN) – New York (JFK) mission on an Aerion AS2 airliner.
(Fuel: $2/gal; 3,500 h annual utilization; $100M purchase price; 3,500 h TBO; 5 % interest rate; 2016 dollars)

In order to calculate ticket prices, more factors have to be taken into account: indirect operating cost (IOC, corresponding to airline management), cabin load factor, fleet utilization, taxes, and profit margin. Assuming

- a yearly IOC of $100M[u]
- an average seat load factor of 75 %,
- roughly $700 for U.S. and U.K. ticket taxes and fees,
- and a profit margin of 20 % (for a relatively risky business),

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[r] This figure was attained by predominantly using seat spacing similar to today's Economy classes.

[s] Other sources even state considerably less than 3 L/seat/(100 km). Differences can often be contributed to varying seat counts.

[t] For comparison, overall CASM for U.S. airlines currently add up to ca. ¢10-¢16, according to DOT Form 41 data. See http://www.planestats.com/cost_analysis/performance_comp [retrieved April 2017].

[u] Assumedly, the bulk of IOC will come from wages. At a rough estimate and assuming a 20-aircraft business, an administrative staff of 500 and an average yearly cost of $100,000 per capita results in yearly expenses of $50M, which would render the IOC guess rather conservative. In this case, $100M would represent about 16 % of overall yearly cost.

a New York City to London return ticket would cost about $9,150 in 2016 U.S. dollars. A recent methodical internet search for premium tickets on return flights between London and New York City, and vice versa, returned Business Class prices of about $2,500-$16,500 and First Class prices of about $4,000-$21,000. Whereas this does not give insights about the actual price distribution of sold tickets and whereas the majority is most probably sold in the lower price ranges, it still indicates that the calculated supersonic tickets would come up in a realistic dimension and would not introduce an all new price segment.

IX. Discussion

a) Methodology

Our market assessment depends on two basic assumptions: First, supersonic flight only takes place over water. Second, passengers of supersonic airliners recruit mainly from premium cabins. In case one or both of the assumptions prove wrong, the market potential will certainly increase. However, we suppose that neither is probable in the foreseeable future for the reasons explained above.

Further, the study takes a two-sided approach. First, a growth of passenger numbers and default percentages of market penetration are imposed top-down to arrive at gross market sizes. This is where many supersonic market assessments conclude, promising optimistic aircraft sales numbers whilst neglecting several crucial parameters. That is why second, we take into account what we deem the most important constraints, namely flight bans, airline environments, and passenger preferences, to design possible airline networks bottom-up. We believe this detailed approach to yield more realistic results.

b) Review of market demand

Eventually, passenger demand for supersonic tickets might turn out higher than expected if the service's appeal to premium passengers is underestimated or if numerous new passengers appear, i.e. tourists, previous non-flyers, or habitual private jet users. However, to increase the chances of realization and to avoid excessive risk for all stakeholders, it appears wise to start off small. It is our opinion that the supersonic airline market has to develop from the cradle and that aiming for severe disruption with a 100-passenger aircraft like Concorde will most likely not turn out successful.

c) Airline fleet planning

Strategic fleet planning usually takes airlines several years and considerable effort, as it firmly establishes the mid-to-long-term orientation of business. Likewise, acquiring and phasing in a new fleet of supersonic airliners will require most diligent planning, as the own premium cabins will probably be cannibalized so that they have to be reconfigured concurrently. Also, the major reason for traditional carriers to operate supersonic airliners, beside prestige, would be to increase profits. In case they expect a simple migration of own passengers from one premium cabin to another without attracting additional demand and without raising overall profit, the business case becomes moot.

d) Airport capacity

A downside to employing numerous small supersonic airliners, as opposed to few large ones, is that they occupy more airport capacity, i.e. flight slots and aircraft stands. Airport congestion being a pressing issue at many metropolitan hubs, particularly in London, this fact might seriously curtail these aircraft's viability.

e) Time benefit of supersonic travel

An aspect not covered here as yet is the varying benefit of supersonic travel with respect to time saving. In certain cases, supersonic flights make more sense than in others. Concorde, for instance, had significantly higher passenger load factors flying westward than flying eastward which was reportedly caused by the fact that the one direction helped save a working day whereas the other only took passengers to London faster [22].

The actual time benefit of supersonic travel is the result of a complicated interaction between numerous factors, whereof the most important are flight timing, flight duration, time shift, working day, and biorhythm. In a recent work, a methodology was presented to quantify the *time benefit* or, conversely, the *time cost of travel* as a weighted sum of travel duration, sleep loss, and working time loss. It is shown that under certain circumstances, it makes more sense for passengers to take the subsonic plane after all. Finally, it is concluded that the timing of a journey is more crucial to its time benefit than flight speed. [23]

For a more in-depth assessment of specific destinations' attractiveness, and for the actual flight scheduling in particular, these interdependencies should be taken into consideration.

X. Conclusion

This work discussed the market for small supersonic airliners from several perspectives: aircraft program economics, airline passenger market, airline networks, the regulatory environment, operating cost, and ticket pricing. It was argued that supersonic designs with lower seat capacity have a better chance of success because passenger demand is limited. The Aerion AS2 supersonic business jet was introduced as a possible instance of a supersonic airliner, serving as a use-case and as an orientation point for the sequential assessment. It was shown that the operating cost of the AS2 allow for ticket prices in the range of regular Business and First Class. The possible market for an AS2 airliner was estimated to span between a few dozens and a few hundred copies.

We conclude that whereas there are numerous caveats, the business case of employing a small-sized supersonic aircraft in airline service does not appear unrealistic under the taken premises.

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