Supersonic Diversions – Assessment of Great-Circle versus Sonic Boom-Restricted Flight Routing

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Overland supersonic flight bans due to the sonic boom are often said to be the reason for civil high-speed aircraft not being able to make a breakthrough. However, there is an apparent lack of studies actually quantifying the disadvantage of law-compliant supersonic flight paths versus optimum overland tracks. This paper presents a framework of city pair-specific flight routes and mission performance simulation for accurate operational assessment of supersonic airplane designs. By application to a supposedly realistic representation of a future civil supersonic air transportation system as a use-case, the impact of rerouting on flight distance, block times, and block fuels is quantified locally as well as globally.

Nomenclature

A388	=	Airbus A380-800	*Pax*	=	Passenger(s)
FA7X	=	Dassault Falcon 7X	*SD*	=	Standard deviation
GC	=	Great circle	*SRQI*	=	Supersonic Rerouting Quality Index
O/D	=	Origin-destination	*SSBJ*	=	Supersonic business jet

I. Background

An object traveling through the atmosphere at velocities higher than the speed of sound inevitably emits compression waves that are perceived as loud bangs on the ground. Those shocks, usually called "sonic booms", are the reason why most developed countries have put bans on supersonic overland flight. Also, they are thought to be the main obstacle for the breakthrough of civil supersonics, beside high operating costs.

In this regard, it is often concluded that future high-speed air transportation can be viable only if said overland speed restrictions are relaxed or entirely lifted[3,4,5]. Accordingly, NASA's current civil supersonic research focuses on sonic boom abatement technology via adaptions to the airframe ("low-boom design") which is considered an enabler for supersonic overland flight[6,7]. To date however, this design strategy has been struggling with fuel efficiency trade-offs as well as with the problem of "super-booms" caused by acceleration.

On the other hand, even if changes in legislation fail to appear due to a lack of political support or technological progress, respectively, supersonic civil flight will still be tolerated above seas and oceans. There are numerous important coastal city pairs having mostly water between them and thus not bearing the need to respect any noise restrictions. Nevertheless, this paper's authors only know of one dated study assessing a conservative scenario where high-speed aircraft would circumvent land masses entirely and still retain considerable time advantages compared to their subsonic counterparts[8]; however in that case, only a limited number of routes was designed, all with regard to airplanes cruising at Mach numbers between 2 and 8 and hence flying considerably faster than examined hereafter.

For the present work, a large quantity of flight paths between the world's major economic centers have been generated with regard to assumedly realistic civil supersonic aircraft characteristics. On each city pairing, variously routed flight missions are simulated for modern subsonic and supersonic airplane designs, resulting in block time and block fuel figures. The findings of flight routing and mission simulation are given for specific city pairs and world regions, all with regard to encountered differences in flight distance, fuel consumption, and mission duration.

In summary, this study introduces an established framework as well as detailed methodologies for accurate flight path-based supersonic mission performance calculation. Results hereof are intended for eventual use in downstream operational research, e. g. in scheduling and cost-estimation models. Also, this paper gives hints on what portions of a possible future civil supersonic air transportation system appear realistic with respect to different legal scenarios.

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II. Route Drafting

A. Methodology

Initially, we assumed that passengers of future high-speed aerial transportation will almost exclusively recruit from business and first class cabins or private business jets, as only these persons will be willing to repeatedly pay the inevitable price premiums on supersonic travel. In order to identify the corresponding global premium passenger flows, a commercial web dialogue[9] was used to compile a database centered on city pair-specific business class/first class airline ticket sales. (Conclusions from said database on premium passenger emergence and a potential supersonic airline market have been drawn in a precedent study[1]. Experiences from another study examining private long haul aircraft let us assume that traffic flows of premium passengers and of business jets are similar[2].)

Furthermore, we chose to ignore existing airways for the present problem, assuming that actual detours on medium-to-long haul routes would be sufficiently small and not perturbing the main trends. Also, plans for harmonizing air traffic management in order to allow for more direct flight routes have been in the making for quite some time, at least in the Western world (namely SESAR[10] and NextGen[11]). These projects might be effective by the time supersonic aircraft enter into service, further playing to our approach.

Moreover, city pairs bearing less than 1000 km of distance were deemed unapt for the present problem and were therefore excluded. For each of the remaining top 250 origin-destination (O/D) pairs regarding total premium ticket revenue in 2012, (the top 10 O/Ds being listed in Table 1), a set of potential flight paths has been conceived by means of the Google Earth platform[12], amounting more than 1500 routings in total. Eventually, each set was to include great circle and supersonic flight paths, both direct and indirect, if needed.

Therefore, we presumed that a future civil supersonic transport would have a design range between 4000 and 5000 nautical miles (nm). For routings approaching 4000 nm or surpassing 5000 nm of distance, we exclusively drafted direct or indirect (intermediate-stop) flight paths, respectively, whereas in between, we drafted both. Supersonic flight paths were designed in up to 3 "basic" and up to 3 cautiously "optimistic" variants for each flight leg, but only if "reasonable" routings were available.

In this context, a "reasonable" routing is one that appears to be still allowing for considerable time savings with regard to the moderate cruise Mach numbers found in most contemporary civil supersonic aircraft designs (*Aerion*[13]: 1.5; *QSST-X*[14,15]: 1.6; *NASA N+1/N+2/N+3*[16]: 1.6-2.0). Thus, for instance, an overwater route between New York and Houston, going around Florida and about doubling flight distance compared to the great circle, was not considered reasonable.

"Basic" refers to routes whose supersonic portions are strictly overwater, whereas on "optimistic" routes, high-speed cruise is permitted above sparsely populated or uninhabited areas like Northern Canada or parts of Australia, all the while maintaining a minimum distance of 50 km to shores or permanent settlements, respectively. (50 km ≈ 30 statute miles were found to be the usual offset of former Concorde routes from coastal areas.)

Since the width of the so-called sonic boom carpet (describing the boom-affected ground surface area along the flight path) is proportional to speed and to altitude[17], the conceived routes are considered valid for airplane designs cruising below Mach 2 and below Flight Level 600 (≈ 20 km altitude), given standard atmospheric conditions.

Aiming to determine the shortest-possible travel durations, all multi-leg missions were planned as point-to-point journeys from the start rather than layover flights, employing stopovers for refueling at suitable airports. Generally, we expect it to be impractical and thus, unlikely for high-speed aircraft to be assigned to hub-and-spoke-kind airline networks, as their single raison d'être is speed; and since said kind of operation incorporates detours plus layover times, significant portions of the best-possible time advantage would inevitably get lost.

An exemplary set of flight routes is shown in Figure 1 for the connection of London and San Francisco. More examples can be found in the appendix.

Origin	Destination	Pax	Revenue (USD)	GC D. (km)
New York	London	383,000	851,000,000	5,555
London	New York	378,000	830,000,000	5,555
London	Singapore	101,000	331,000,000	10,886
Singapore	London	105,000	362,000,000	10,886
Dubai	London	119,000	287,000,000	5,504
London	Dubai	121,000	298,000,000	5,504
Paris	New York	95,000	280,000,000	5,848
New York	Paris	95,000	283,000,000	5,848
Los Angeles	London	90,000	254,000.000	8,781
London	Los Angeles	88,000	244,000.000	8,781
Hong Kong	London	74,000	218,000.000	9,647
London	Hong Kong	76,000	217,000.000	9,647
Johannesburg	London	70,000	197,000.000	9,046
London	Johannesburg	72,000	206,000.000	9,046
London	Sydney	42,000	190,000.000	17,015
Sydney	London	47,000	209,000.000	17,015
London	San Francisco	68,000	193,000.000	8,638
San Francisco	London	69,000	203,000.000	8,638
Houston	London	58,000	195,000.000	7,780
London	Houston	59,000	197,000.000	7,780

Table 1. Top 10 O/Ds of premium ticket revenue, 2012

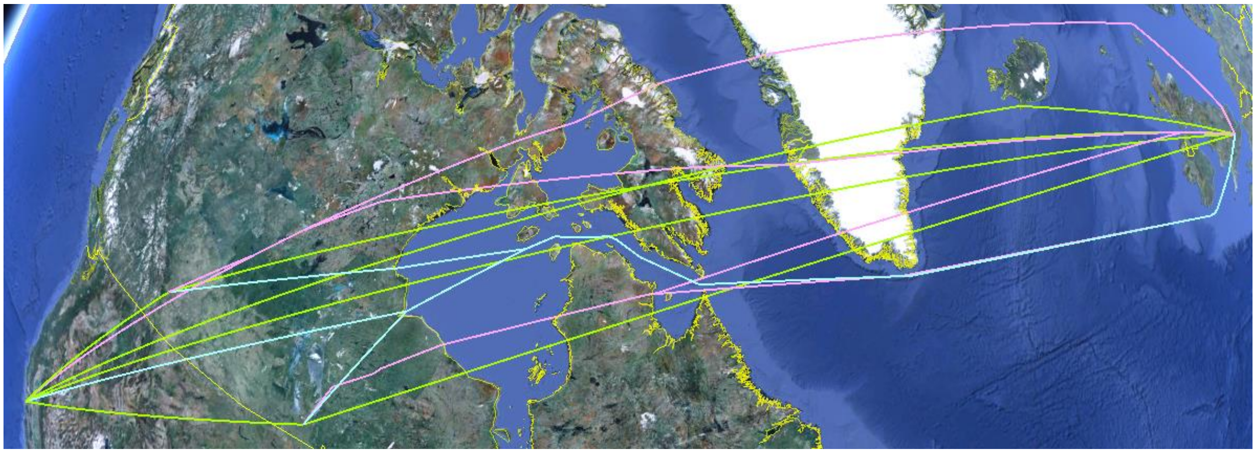


Figure 1. Direct and indirect flight routes between London and San Francisco:
Great circles (green), basic diversions (blue), and optimistic diversions (purple). [Credit: Google Earth[12]]

B. Results

226 (basic) + 5 (optimistic only) of the 250 city pairs taken into consideration were found to provide for promising supersonic flight routings, representing a quota of 90 % (basic) and 92 % (optimistic), respectively. Accordingly, 8 to 10 % of city pairs did not appear to cater for effective supersonic diversions. Most of the latter are located in Eurasia and North America.

The mean detour needed for supersonic flight paths comes down to 6 % (standard deviation: 7.5 %) on the 920 basic flight legs and to 4 % (SD: 4.5 %) on the 384 optimistic ones.

The distance percentage of segments without speed restriction averages on 83 % both for the basic (SD: 16 %) and for the optimistic (SD: 10.6 %) routings. Hereby, it is worth mentioning that certain varying distances at the beginning and at the end of any supersonic mission will be flown subsonically anyway on account of the acceleration and deceleration flight phases. This means that the average quota of realizable to maximum high-speed distance will always exceed the values mentioned.

A statistical summary of detours and unrestricted distance percentages of the drafted supersonic routes is depicted in Figures 2 and 3. (For instance, it can be read from Figure 2 that for 85 % of all routes, the detour distance adds up to less than 10 %. Figure 3 shows e. g. that the distance percentage of unrestricted flight amounts to more than 80 % for about 70 % of all routes. Note that the terms “unrestricted” and “supersonic” are used interchangeably as in most cases, they represent nearly the same distances.) The graphs reveal that for the majority of city pairings, diverted supersonic routes are expected to require relatively small trade-offs compared to great circle routings either concerning detours or concerning high-speed cruise percentage (but not yet both). At the same time, we need to recall that for up to 10 % of O/Ds, supersonic rerouting was deemed impractical from the start; these failed attempts are not represented in the Figures.

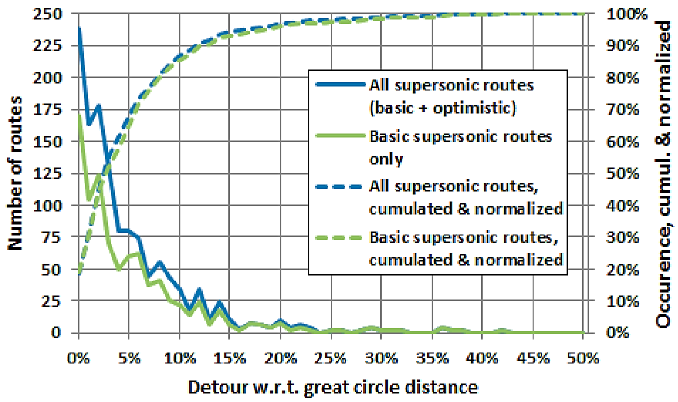


Figure 2. Distribution of detours

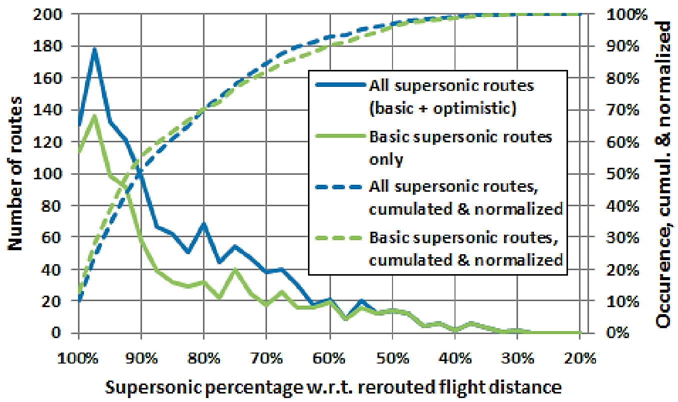


Figure 3. Distribution of unrestricted distance percentages

19 % of the drafted supersonic flight paths contain one intermediate overland segment, 4 % contain two, and 1 % contain three. For some city pairings, these speed-restricted segments appear indispensable in order to avoid excessive detours or time losses, respectively.

Europe–Middle East connections, for instance, whereas being of high importance themselves, are probably essential for opening up the markets between Western Europe and Southeast Asia or Oceania, respectively. However, they will probably only be useful if they are directed over the Mediterranean Sea and only if there is a second supersonic acceleration after crossing the densely populated Eastern Mediterranean coastlines (i. e., another supersonic cruise segment above Arabian deserts and/or the Arab Gulf), as detours still come out considerable and supersonic portions are meager.

Yet with regard to operational practice, each acceleration through the transonic drag rise known as the “sound barrier”, preceded by a descent phase and followed by a supersonic climb, will compromise engine life cycle, fuel reserves, and not least, passenger comfort.

In regard to assessing the quality of rerouted supersonic flight paths and summarizing their primary deficits, the Supersonic Rerouting Quality Index SRQI is introduced. We arbitrarily define:

- *The quality parameter of detour* QP_D to be 1 for 0 % distance increase compared to the great circle route, and 0 for 100 % distance increase, having a linear gradient between these values.
- *The quality parameter of restriction percentage* QP_R to be 1 for 100 % unrestricted flight percentage and 0 for 0 % unrestricted flight percentage, having a linear gradient in between.
- *The quality parameter of segmentation* QP_S to be 1 for zero speed-restricted intermediate segments, 0.75 for one segment, 0.5 for two segments, and 0.25 for three segments.
- *The quality parameter of intermediate stops* QP_I to be 1 for zero additional stops compared to great circle routing, 0.5 for one additional stop, and 0 for two or more additional stops. (Remark: Owing to atmospheric variability, i. e. mainly winds, it proved hardly possible to determine if the envisaged flight routing is operable simply based on aircraft design range. Thus, we decided to employ results from the subsequent mission performance simulation in order to verify routing operability. This shortcoming can be considered small since it was found to result in significant SRQI differences only on very few city pairs.)

Subsequently, the flight path-specific Supersonic Rerouting Quality index is calculated by:

$$SRQI_i = QP_{D,i} \cdot QP_{R,i} \cdot QP_{S,i} \cdot QP_{I,i} \cdot 100 \quad (1)$$

SRQI is intended to express the capability of the applied supersonic flight path design methodology relative to optimum great circle routing, independent of aircraft flight performance (except for, to some extent, range). Figure 4 summarizes the maximum values of SRQI for the top 250 city pairs, including O/Ds allowing for no reasonable supersonic rerouting (being accounted for with SRQI = 0). It can be seen that for a multitude of flight paths, the values of SRQI rank high, showing relatively small trade-offs compared to great-circle routing. SRQI averages out at 65 and at 61 for the respective optimistic and basic scenarios. Values of SRQI for the top 25 O/D pairs are listed in the Appendix.

Apart from all aspects of routing quality, distances and segmentations still need translating into flight times and figures of fuel consumption for the assessment of their actual impact on operability. This problem becomes non-trivial at the latest for multiple supersonic cruise segments.

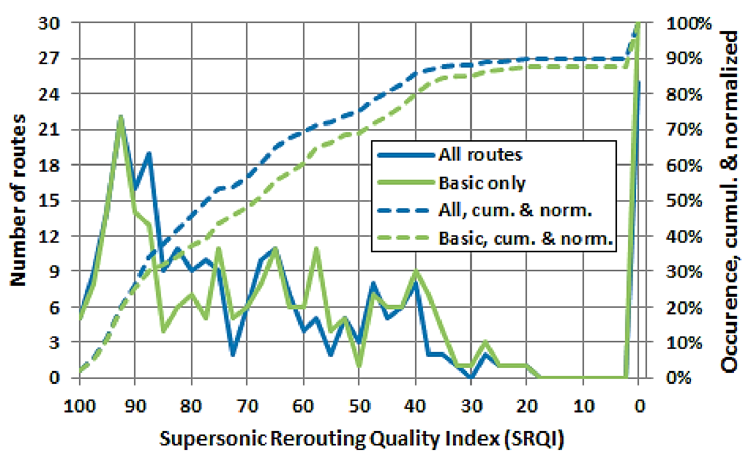


Figure 4. Distribution of maximum SRQIs for the Top 250 O/D pairs

III. Mission Performance Calculation

A. Methodology

In order to assess supersonic flight missions on the previously defined flight routes and to attain reliable figures of mission duration and fuel consumption, a proprietary flight physics-based mission performance tool was programmed. By design, it simulates missions in arbitrary subsonic-supersonic segmentation and in coordinate-specific atmospheric conditions. Its inputs are as follows:

- Flight routes, exported from Google Earth.
- An atmospheric database, containing global mean air pressures, densities, temperatures, and winds, provided by DLR's Institute of Atmospheric Physics (DLR-PA).
- An airports database including elevations and mean taxi times, the latter coming from EUROCONTROL Central Office of Delay Analysis (CODA) data[18].
- Aircraft performance maps (aerodynamics, engine, weights, operational procedures).

The HISAC-A supersonic business jet (SSBJ) from the pan-European HISAC (Environmentally friendly HIgh-Speed AirCraft) project[19] was employed as an example of a Mach 1.6, 4000-nm-range aircraft, in our opinion adequately representing the initial instance of a civil supersonic airplane in the foreseeable future. Its flight performance characteristics were emulated using proprietary documentation.

For the simulation of subsonic missions, another mission performance tool by DLR called Trajectory Calculation Module (TCM) was employed. It uses the great circle flight routes from Google Earth as well as the atmospheric and airports databases mentioned, plus EUROCONTROL Base of Aircraft Data (BADA)[20] for flight performance specifications of the subsonic reference aircraft.

Regarding the latter, we took the latest high-speed long-range civil aircraft that were available in BADA, which turned out to be the Airbus A380-800 as a highly fuel-efficient and the Dassault Falcon 7X as a high-end business jet. Technical specifications of all aircraft models used are listed below in Table 2.

The rerouted flight paths were solely applied to supersonics. Apart from Mach 1.6 above water, the overland segments were simulated for two different cruise velocities:

In the first run, Mach 0.99 is taken as a marginally subsonic speed that still provides for design range, complying with laws anywhere in the world. Secondly, an appropriate cruise Mach number is determined dynamically for each overland segment in order to make the sonic boom dissipate at an arbitrary altitude of 10,000 feet because of differences in temperature and consequently, speed of sound. This velocity, usually being called the Cutoff-Mach number[21], averages at around Mach 1.15 for the given constraints. We found said cruising mode to reduce range by up to 10 % for the HISAC-A SSBJ, however.

For the sake of assessing further legal and operational scenarios, respectively, the supersonic aircraft was additionally deployed on great circle missions cruising at Mach 1.6, at Mach 0.99, and at Cutoff Mach. Thus, in summary, five variations of speed and routing were simulated.

In contrast, the subsonic aircraft were solely sent on great-circle routed missions cruising at Mach 0.85 for the A380 and at Mach 0.9 for the Falcon 7X, respectively.

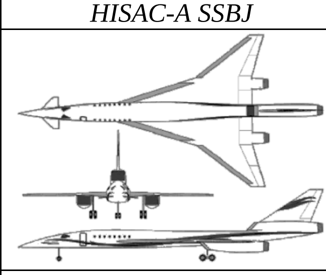
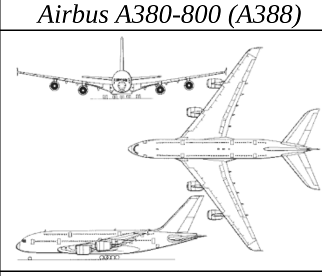
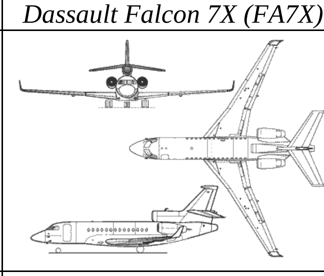
	HISAC-A SSBJ	*Airbus A380-800 (A388)*	*Dassault Falcon 7X (FA7X)*
			
Seats, Typ. / Max.	8 / 8	525 / 853	12 / 16
Max. Mass	51,095 kg	560,000 kg	31,300 kg
Max. Fuel Mass	26,900 kg	257,280 kg	14,488 kg
Length · Span	36.8 m · 18.5 m	72.7 m · 79.8 m	23.4 m · 26.2 m
Design Range	4000 nm (7408 km)	8500 nm (15742 km)	6000 nm (11112 km)
Design Mach	1.6 and 0.95 (overland)	0.85	0.8 (max.: 0.9)
T/O Field Length	6500 ft	9020 ft	5555 ft
Entry Into Service	2015 (by design)	2007	2007

Table 2. Technical specifications of aircraft employed for mission performance simulation

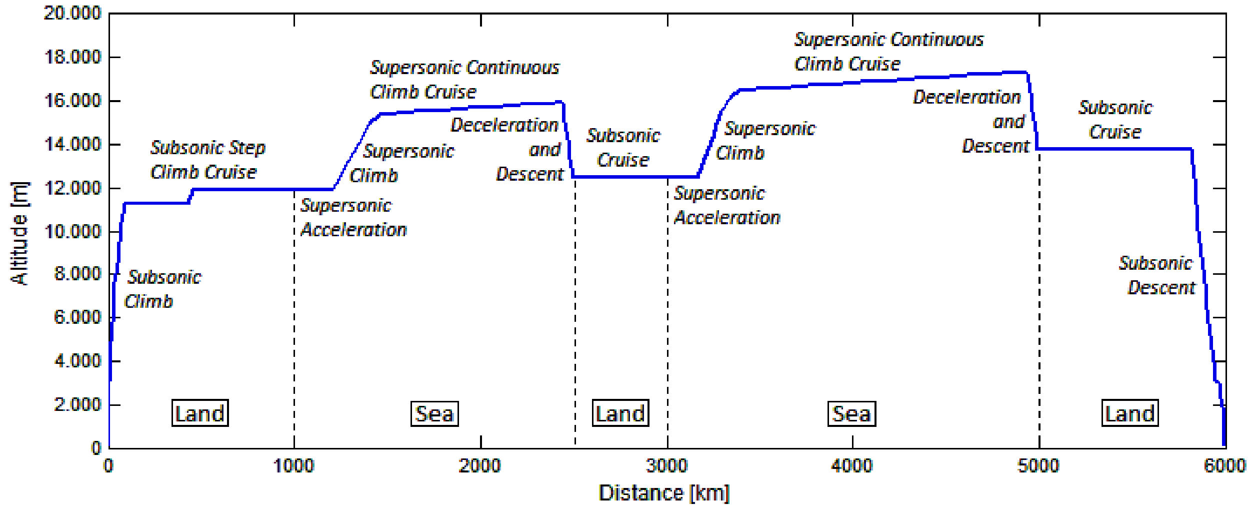


Figure 5. Generic supersonic mission trajectory with one intermediate overland segment

Figure 5 displays a generic example of a simulated supersonic mission trajectory. It features a leading, an intermediate, and a finishing subsonic segment, all flown in step climb cruise mode (in order to comply with subsonic air traffic and mandatory flight levels, respectively), and two supersonic segments flown in continuous climb cruise, ever using altitudes of optimum efficiency whilst preserving a minimum of excess thrust for maneuverability.

Each of the over 1500 flight paths was simulated in both directions, applying different speed settings as well as different aircraft. All O/D pairs were subsequently assigned their corresponding flights and missions, allowing for the identification of aircraft-specific minimum-block time flight routing.

On multi-legged missions, the maximum refueling duration (excluding taxi times) was assumed to be 20 minutes for the Falcon 7X as well as for the HISAC-A and 120 minutes for the A380. Actual refueling times were calculated with respect to the subsequent flight leg's fuel requirement by a simple linear correlation.

For the summarization of results, three legal scenarios regarding supersonic overland flight were developed:

- *Full Permit scenario:* General clearance for supersonic overland flight (also representing the operating environment of envisioned low-sonic boom supersonic aircraft). Exclusive use of great circle routes.
- *Mixed Permit scenario:* Cutoff-Mach overland flight and supersonic flight above uninhabited areas.
- *No Permit scenario*: Subsonic overland flight.

In case no supersonic flight paths were available for a city pairing, the great circle routed Cutoff-Mach or subsonic missions were taken into account for the respective Mixed Permit or No Permit scenarios. In case Cutoff-Mach flight failed due to aircraft range, the respective flight paths with subsonic overland flight were employed.

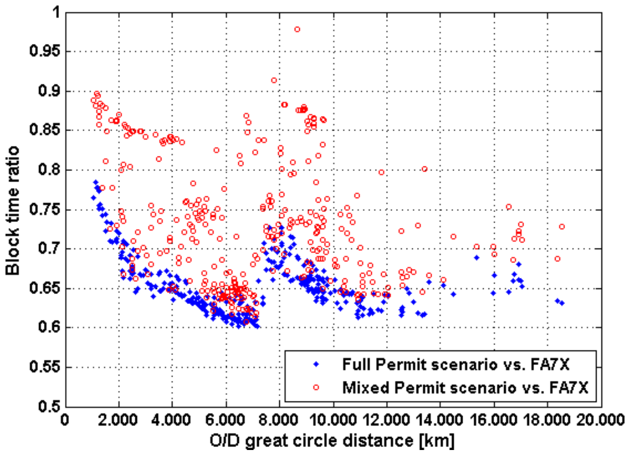
B. Results

The following assessment is focused on block times and block fuels, since these are commonly considered the fairest and most important measures for cost/benefit-analyses regarding faster air travel. When examining flight offerings, passengers as well as airlines will primarily weigh flight schedules and the resulting total durations against the cost of travel whereof fuel will supposedly cause the paramount share.

Statistical summaries of the findings regarding block times and block fuels are documented in the appendix' Tables 3 and 4, respectively. Generally, the underlying missions for the O/D pairs in the respective scenarios are always the fastest ones available, not the most efficient ones. In the following, particular observations are discussed.

Supersonic vs. subsonic aircraft: Comparing the HISAC-A in the Full Permit scenario to the Falcon 7X, it shows that the block time ratio is 65 % on average and 60 % at best (i. e., time gains are 35 % or 40 %, respectively). This can be attributed to the influence of taxiing and refueling times as well as to the shorter flight range (see Figure 6 for the distribution of flight direction-averaged values; note the jump in the efficiency frontier, caused by technical stops). Thus, we tend to assume that Mach 1.6 aircraft will probably not be able to "cut travel times in half" on a regular basis even with supersonic overland flight permission, given that their subsonic counterparts will always be superior on range.

In the Mixed Permit (see Fig. 6) and No Permit scenarios, the mean block times relative to the FA7X rise to 73 % and 78 %, respectively, with values revealing much greater spread. As expected, there are city pairs allowing for negligible time loss on supersonic flight paths, whereas on others, flying detours makes very little sense.



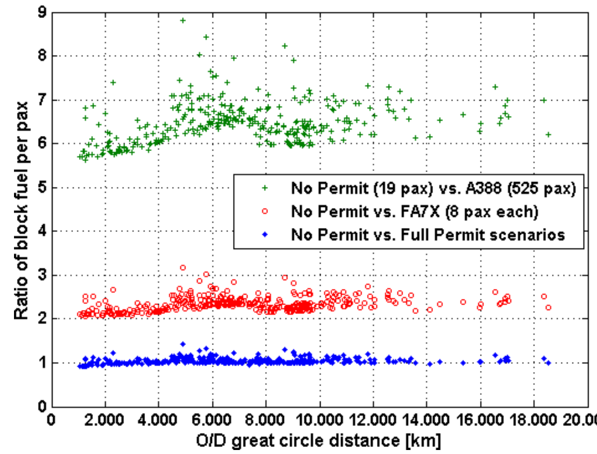


Figure 6. Block time ratios over GC distance

Figure 7. Ratios of block fuel/pax over GC distance

Fuel consumption (see Fig. 7) of the HISAC-A SSBJ comes out about twice to thrice compared to the FA7X, depending on the underlying scenario, which marks a trend for the operational model of private aviation. In regard to airline operations, proprietary documentation cites the HISAC-A to consume about 5 % more fuel in case of a high-density 19-passenger payload. This means that fuel per passenger would still be at least 5.5 times as high compared to the disparately more efficient A388 in a typical three-class layout.

Scenario comparison: Full Permit flight often yields significant time gains relative to the Mixed Permit and No Permit scenarios, averaging on 10 % and 15 %, respectively. Assuming similar flight performance, the ability to always yield comparable time gains on varying routes makes the case for low-sonic boom aircraft.

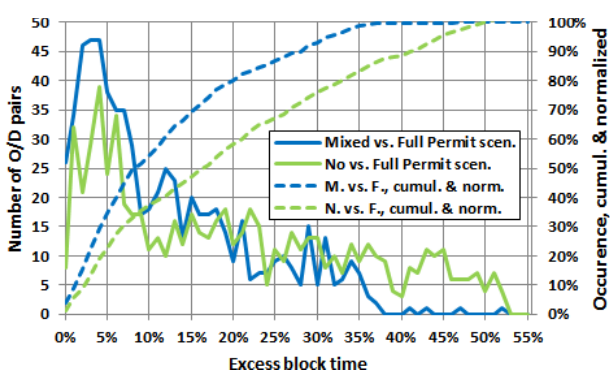
When ruling out top-speed overland cruise, the Mixed Permit scenario can deliver more than 3 hours of time advantage compared to the No Permit one, the mean advantage being mere 25 minutes though.

In many cases however, time trade-offs for scenarios of restriction are relatively small, rendering supersonic aircraft solely trimmed for efficiency particularly worthwhile. For instance, this relationship can be observed for the important cluster of Western Europe to North American East Coast routes, appearing in Figure 6 at around 6,000 km. More than 50 % of O/D pairs require less than 10 % of additional block time when comparing Mixed Permit scenario to Full Permit scenario missions (see Fig. 8); yet for No Permit, the distribution looks somewhat worse.

Differences in block fuel span up to 23 % around the mean value for specific city pairs. In our opinion, this will have a rather minor impact on operational benefit for future high stakes business applications. (See also Fig. 9.)

Cutoff-Mach vs. subsonic cruise: Comparing Cutoff-Mach to Mach 0.99 cruise on single flight legs (apart from scenarios), time gains of 52 minutes on pure overland stages and of 31 min on rerouted flight paths are yielded at best. When challenging the FA7X and the A388 on great circle missions, the maximum time advantage climbs to 92 and 114 min, respectively. On the prototypical New York–Los Angeles coast-to-coast itinerary, block time was calculated to shorten by 71 min westbound and by 53 min eastbound relative to the A388, by 57 or 39 min relative to the FA7X, and by 31 or 21 min relative to Mach 0.99 cruise, respectively.

Thus, Cutoff Mach appears to be a valuable asset for supersonic operations in sonic boom-restricted environments. As mentioned before, time gains are traded against additional fuel consumption though.



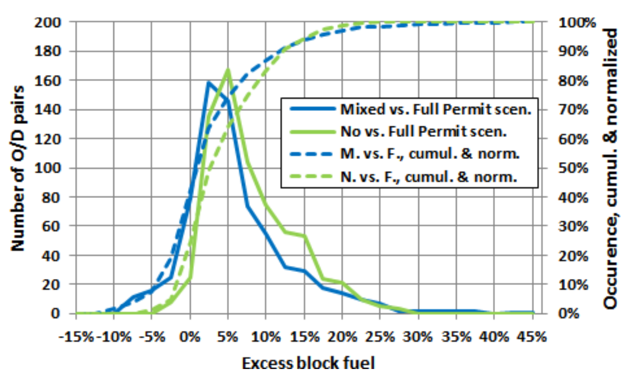


Figure 8. Distribution of excess block times

Figure 9. Distribution of excess block fuels

IV. Discussion

In the following, miscellaneous issues related to this paper are debated:

A. Statistical significance

According to ADI data[9], the top 250 city pairs account for 57 % of the global revenue generated by premium airline tickets. This figure underlines the statistical significance of results obtained from the present framework, at least in view of airline operations. However, we assume that the occurrence of non-scheduled business jet operations will be largely proportional to premium airline travel.

B. Atmospheric database

Instead of International Standard Atmosphere (ISA), we chose to employ globally distributed mean atmospheric data including winds. This was found to significantly improve the validity of flight performance simulation, more than ever on long-haul routes. On the extreme end, block times were calculated to differ between flight directions by 3 hours and 22 minutes for the FA7X on the Houston–Perth city pair. The aircraft's eastbound performance was compromised even more by requiring an additional refueling stop.

D. Calibration of SRQI parameters

For future applications, e. g. quick guessing of block times, SRQI should be calibrated to better fit specific supersonic aircraft designs by adjusting the values of the quality parameters QP_i in order to enhance the correlation between SRQI and the ratio of unrestricted and rerouted block times. Figure 8 depicts a non-calibrated and thus, weak correlation for single leg missions of the No Permit scenario.

E. ETOPS

As an additional specification, we documented expected ETOPS (Extended-range Twin-engine Operation Performance Standards) requirements for each flight leg. Hence, ETOPS routes can be taken into account optionally in follow-up studies. This was not considered necessary at present, as all examined aircraft featured at least three engines.

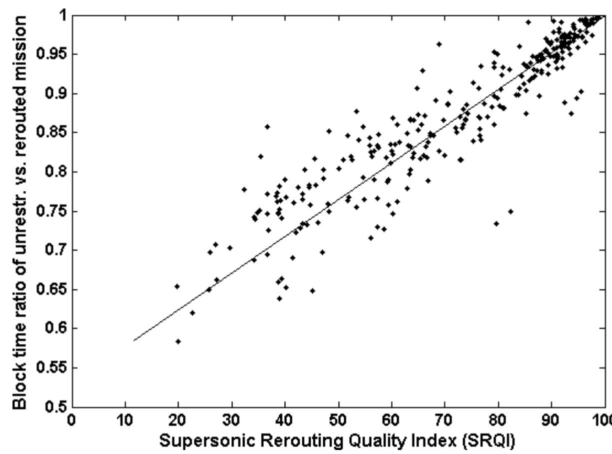


Figure 8. Block time ratios relative to SRQI

C. Cutoff Mach

Cutoff-Mach flight was taken into account because it appears to be tolerated in most parts of the world, as regulations oftentimes merely declare that the sonic boom must be kept from reaching the ground. In Germany for instance, this prescription can be found in Luftverkehrsordnung (LuftVO) §11a and §11b. In the US though, Federal Aviation Regulation (FAR) 91.817 entirely prohibits civil supersonic flight. Unfortunately, we have not been able to get hold of a global sonic boom laws compendium, for it could have been included in this study.

F. Benefit of supersonic overland flight and low-boom design, respectively

Our findings do not exhibit any indications that lifting overland flight bans can decisively enable the realization of a future high-speed air transportation system. Evidently, there are various important city pairs like Rome–Beijing or New York–Seattle that are hardly imaginable to operate without high-speed overland permission. On the other hand, we encountered even more itineraries allowing for nearly undisturbed supersonic flight and requiring insignificant handicaps regarding flight time. Between those extremes and for the majority of O/D pairs, the picture becomes unclear as time and fuel trade-offs have to be considered.

Thus, conclusions on the more promising aircraft design strategy – low-boom in expectation of clearance for supersonic overland cruise, or efficient high-boom needing detours – can only be made on the basis of in-depth analyses and in knowledge of low-boom aircraft mission performance characteristics. At best, a comparative study regarding the operational environment would include a family of supersonic aircraft with varying specifications, yet designed by the same group and coming in pairs of one low-boom and one traditionally-conceived jet.

Incidentally, it remains our opinion that low-boom best fits to non-scheduled, non-commercial operations, i. e., private flight, owing to this operational model's need for flexibility and its comparative inelasticity to additional expenditures. In contrast, commercial operators, i. e., airlines or fractional aircraft providers, can standard deploy their supersonic jets on long-haul overwater routes and are thus thought to prefer optimum efficiency.

V. Conclusion

This paper presented a framework for detailed mission performance assessment regarding supersonic aircraft in varying regulatory environments.

Therefor, a methodology for supersonic flight path design was pointed out, its adaptation eventually delivering a large number of flight tracks between the world's major economic centers. The results are suggested to contain valid routings for diverse legal scenarios and for subsonic or supersonic, low-boom or traditional, high performance civil airplanes exhibiting cruise speeds of up to Mach 2 and flight altitudes of up to 20,000 meters. This constitutes a singular database for supersonic operations research.

Concerning the results of drafting, it was found that on some city pairings, rerouting makes little sense. For the majority of them however, rerouted supersonic flight paths were concluded to require relatively small trade-offs, i. e., detours, subsonic segments, and additional intermediate stops, against optimum routes.

Next, a flight performance simulation model was introduced, being tailored for missions following the described flight paths and incorporating global atmospheric data including winds. Based on different scenarios regarding sonic boom laws, the application of the model to an emulation of the HISAC-A supersonic business jet yielded figures of block times and block fuels. Those were compared to analogous results for the Airbus A380 airliner and the Dassault Falcon 7X business jet that were calculated using our established Trajectory Calculation Module (TCM) mission performance model.

The simulation outcomes were analyzed statistically as well as specifically, resulting in ambivalent findings. Whereas block time advantages of supersonic flight were sometimes marginal and often significant, they were clearly traded against a multiple of fuel consumption. Moreover, even though flight duration discrepancies were oftentimes found to be high on varying legal scenarios and routings, respectively, rerouted flight was considered a worthwhile alternative for the majority of city pairs.

Looking forward, the introduced framework is intended for use on further supersonic aircraft designs fulfilling the described requirements. Ultimately however, it has the purpose of producing reliable data for operational research and assessment, especially with regard to models of flight schedule conception, airline network design, and operations cost setup. Rather than building on simplistic estimations, economic research and not least, aircraft design is expected to benefit from accurate and adaptive operational performance modeling.

Appendix

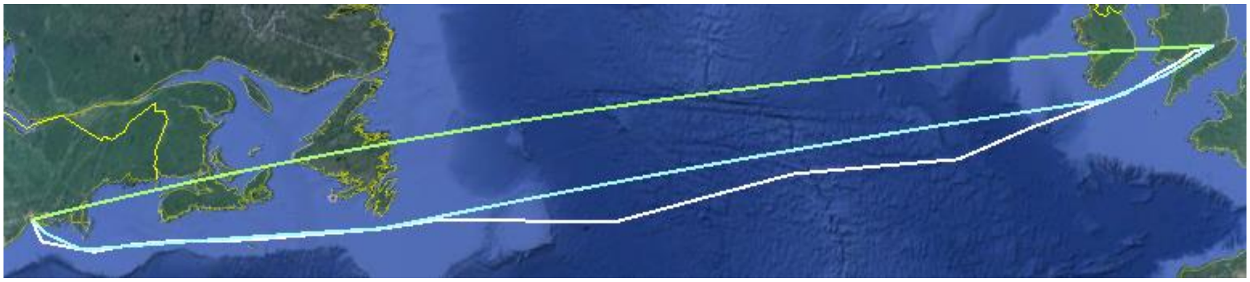


Figure 10. New York–London flight routes: Great circle (green), own design (blue), former track of the Aérospatiale-BAC Concorde supersonic airliner (white). [Credit: Google Earth[12]]

Figure 11. Paris–Tokyo flight routes (via Norilsk): Great circle (green), own optimistic designs (purple). [Credit: Google Earth[12]]

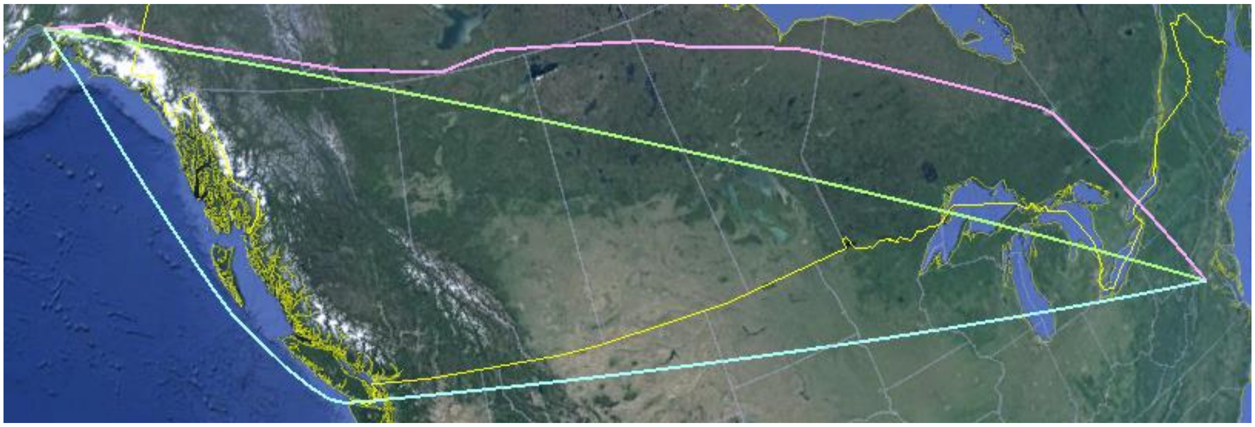


Figure 12. Anchorage–Washington flight routes: Great circle (green), own basic design (blue), own optimistic design (purple). [Credit: Google Earth[12]]

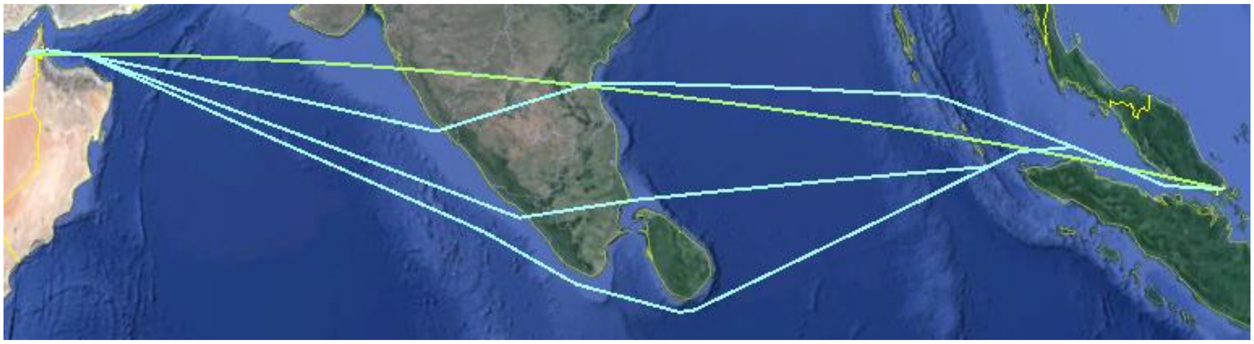


Figure 13. Dubai–Singapore flight routes: Great circle (green), own designs (blue). [Credit: Google Earth[12]]

Block Times			Min.	Max.	Mean	Median	SD
HISAC-A emulation, Full Permit scenario, 8 pax		[min]	73	811	319	287	152
HISAC-A emulation, Mixed Permit scenario, 8 pax		[min]	86	930	356	303	169
HISAC-A emulation, No Permit scenario, 8 pax		[min]	92	1080	381	330	186
FA7X, great circle routes, Mach 0.9 cruise, 8 pax		[min]	98	1328	494	469	238
A388, great circle routes, Mach 0.85 cruise, 525 pax		[min]	103	1422	517	492	256
Block times in Full Permit scenario …	… w.r.t. Mixed Permit scenario	[min]	-188	12	-36	-25	36
		[%]	66	103	90	92	7.5
	… w.r.t. No Permit scenario	[min]	-269	7	-62	-43	57
		[%]	66	102	85	85	10.0
	… w.r.t. FA7X	[min]	-517	-21	-175	-167	90
		[%]	56	81	65	65	4.5
	… w.r.t. A388	[min]	-611	-25	-198	-186	107
		[%]	54	77	63	62	4.5
Block times in Mixed Permit scenario …	… w.r.t. No Permit scenario	[min]	-194	0	-25	-14	32
		[%]	71	100	94	95	5.3
	… w.r.t. FA7X	[min]	-438	-3	-138	-129	84
		[%]	56	99	73	72	8.3
	… w.r.t. A388	[min]	-533	-14	-161	-149	101
		[%]	54	95	70	69	8.2
Block times in No Permit scenario …	… w.r.t. FA7X	[min]	-400	2	-113	-109	80
		[%]	57	100	78	77	10.7
	… w.r.t. A388	[min]	-522	-9	-136	-126	96
		[%]	54	96	75	74	10.4

Table 3. Statistics of mission block time on top 250 O/D pairs

Block Fuels per Passenger			Min.	Max.	Mean	Median	SD
HISAC-A emulation, Full Permit scenario, 8 pax		[kg/pax]	481	7644	2828	2782	1424
HISAC-A emulation, Mixed Permit scenario, 8 pax		[kg/pax]	465	7712	3003	2890	1511
HISAC-A emulation, No Permit scenario, 8 pax		[kg/pax]	437	8519	2969	2879	1526
FA7X, great circle routes, Mach 0.9 cruise, 8 pax		[kg/pax]	204	3374	1255	1200	626
A388, great circle routes, Mach 0.85 cruise, 525 pax		[kg/pax]	34	547	201	191	1526
Block fuels in Full Permit scenario …	… w.r.t. Mixed Permit scenario	[kg/pax]	-1007	166	-175	-114	185
		[%]	79	106	94	96	4.9
	… w.r.t. No Permit scenario	[kg/pax]	-1426	216	-142	-69	226
		[%]	70	112	96	97	6.1
	… w.r.t. FA7X	[kg/pax]	268	4270	1572	1570	802
		[%]	197	249	225	224	10.1
	… w.r.t. A388	[kg/pax]	448	7097	2627	2593	1323
		[%]	1230	1570	1403	1400	65.1
Block fuels in Mixed Permit scenario …	… w.r.t. No Permit scenario	[kg/pax]	-882	784	34	28	166
		[%]	77	123	102	101	5.4
	… w.r.t. FA7X	[kg/pax]	261	4602	1748	1675	892
		[%]	200	282	238	238	13.9
	… w.r.t. A388	[kg/pax]	432	7165	2802	2691	1402
		[%]	1252	1770	1488	1484	88.1
Block fuels in No Permit scenario …	… w.r.t. FA7X	[kg/pax]	233	5208	1714	1668	912
		[%]	199	317	234	233	18.1
	… w.r.t. A388	[kg/pax]	403	7995	2768	2679	1427
		[%]	1247	1991	1463	1455	115.1

Table 4. Statistics of mission block fuel per passenger on top 250 O/D pairs

			Subsonic				Routing		Supersonic: HISAC-A, 8 pax					
			FA7X, 8 pax		A388, 525 pax		SRQI		Full Permit		Mixed Permit		No Permit	
Origin	**Destination**	**Great circle distance [km]**	**Block time [h:min]**	**Block fuel/ pax [kg]**	**Block time [h:min]**	**Block fuel/ pax [kg]**	**optimistic**	**basic**	**Block time [h:min]**	**Block fuel/ pax [kg]**	**Min. block time [h:min]**	**Resp. block fuel/pax [kg]**	**Min. block time [h:min]**	**Resp. block fuel/pax [kg]**
New York	London	5555	6:08	900	6:25	143	91	91	4:00	2130	4:06	2160	4:07	2148
London	New York		7:08	1070	7:30	171	91	91	4:15	2334	4:25	2400	4:29	2389
London	Singapore	10886	12:06	1806	12:03	297	63	63	7:50	4137	9:30	4839	10:03	4803
Singapore	London		13:10	1988	13:14	333	63	63	8:07	4385	9:52	5170	10:32	5117
Dubai	London	5504	6:51	1038	7:10	165	39	39	4:08	2278	4:57	2721	5:32	2630
London	Dubai		6:04	901	6:22	144	39	39	3:57	2095	4:38	2412	5:05	2298
Paris	New York	5848	7:26	1129	7:48	180	92	92	4:22	2471	4:30	2529	4:32	2519
New York	Paris		6:26	946	6:44	151	92	92	4:12	2263	4:18	2290	4:20	2277
Los Angeles	London	8781	9:30	1496	9:59	239	64	61	6:29	3404	7:12	3489	7:32	3392
London	Los Angeles		10:27	1647	10:57	262	64	61	6:43	3616	7:33	3754	7:59	3681
Hong Kong	London	9647	12:20	1812	12:06	297	39	39	7:37	3926	10:11	4469	11:19	4054
London	Hong Kong		10:15	1625	10:45	259	39	39	7:09	3604	9:13	3927	10:08	3530
Johannesburg	London	9046	10:16	1636	10:41	258	82	82	6:51	3637	8:48	4074	9:08	4591
London	Johannesburg		9:57	1583	10:21	251	82	82	6:58	3605	8:37	4298	9:08	4514
London	Sydney	17015	18:22	2869	20:16	455	76	72	12:27	6574	13:43	7146	14:34	7207
Sydney	London		19:48	3152	21:49	499	76	72	12:39	6907	14:10	7595	15:23	7877
London	San Francisco	8638	10:10	1606	10:40	256	69	66	6:34	3457	7:15	3683	7:38	3730
San Francisco	London		9:29	1483	9:58	237	69	66	6:28	3491	7:10	3474	7:32	3378
Houston	London	7780	8:17	1275	8:40	203	90	90	6:13	2972	6:17	3233	6:21	3213
London	Houston		9:31	1496	9:59	238	90	90	6:24	3190	6:33	3561	6:40	3543
New York	Los Angeles	3984	5:27	780	5:41	124	27	27	3:26	1636	4:30	1882	5:01	1714
Los Angeles	New York		4:29	642	4:42	103	27	27	3:04	1485	3:49	1564	4:11	1401
Washington	London	5971	6:21	953	6:40	152	89	89	4:05	2270	4:13	2298	4:16	2281
London	Washington		7:27	1136	7:50	181	89	89	4:22	2488	4:35	2573	4:39	2553
New York	San Francisco	4162	5:35	810	5:49	129	23	23	3:27	1703	4:35	1956	5:07	1784
San Francisco	New York		4:44	674	4:58	108	23	23	3:14	1563	4:03	1657	4:25	1480
Boston	London	5255	5:40	844	5:56	135	92	92	3:39	1979	3:43	2008	3:45	1998
London	Boston		6:44	1009	7:04	161	92	92	4:00	2180	4:10	2239	4:14	2227
London	Chicago	6362	7:51	1198	8:14	191	80	70	4:39	2704	5:01	2837	5:39	2994
Chicago	London		6:56	1046	7:17	167	80	70	4:22	2495	4:40	2568	5:03	2583
Hong Kong	New York	12990	14:46	2228	16:21	356	85	45	9:16	5325	9:45	5531	12:14	5583
New York	Hong Kong		15:11	2307	16:40	368	76	45	9:42	5657	10:20	5953	13:34	6222
Los Angeles	Sydney	12050	14:31	2248	15:42	355	99	99	8:57	4900	8:58	4889	9:00	4880
Sydney	Los Angeles		12:54	1969	12:55	327	99	99	8:32	4692	8:34	4700	8:36	4688
Sao Paulo	New York	7636	8:53	1384	9:14	218	93	93	6:18	2965	6:46	3092	7:06	3010
New York	Sao Paulo		8:32	1317	8:53	208	93	93	6:21	2932	6:36	3052	6:55	2965
London	Miami	7122	8:57	1394	9:23	222	94	94	5:11	3112	5:17	3131	5:20	3113
Miami	London		7:28	1140	7:47	181	94	94	4:47	2816	4:50	2817	4:52	2805
New York	Zurich	6327	6:49	1021	7:08	163	87	87	4:23	2455	4:35	2513	4:38	2488
Zurich	New York		7:55	1219	8:19	195	87	87	4:36	2702	4:52	2802	4:58	2776
Cape Town	London	9648	11:38	1725	11:18	278	96	96	7:32	3899	8:19	4447	8:21	4433
London	Cape Town		10:33	1696	11:00	268	96	96	7:20	3857	8:17	4184	8:32	4383
Luanda	Lisbon	5760	6:34	1014	6:50	161	73	73	4:06	2274	4:36	2542	5:02	2992
Lisbon	Luanda		6:30	986	6:47	157	73	73	4:12	2276	4:43	2543	5:12	3059
Paris	Los Angeles	9123	10:46	1718	11:18	273	67	59	6:52	3782	7:41	4006	8:23	4026
Los Angeles	Paris		9:53	1559	10:23	249	67	59	6:45	3573	7:26	3719	8:02	3616
London	Toronto	5724	7:12	1084	7:33	173	87	78	4:17	2401	4:30	2482	4:56	2603
Toronto	London		6:14	932	6:33	149	87	78	3:58	2197	4:10	2273	4:26	2281
Singapore	Sydney	6288	6:47	1040	7:04	165	65	59	4:30	2502	4:40	2576	5:42	2602
Sydney	Singapore		7:19	1152	7:37	182	65	59	4:25	2558	4:39	2666	5:40	2939

Table 5. Top 25 O/D pairs regarding premium ticket revenue with respective operational figures

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