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Analysis of flight profile and sonic boom population response of updated aerodynamic configuration for hypersonic passenger transport

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Abstract
The DLR concept SpaceLiner for a high-speed rocket-propelled launcher and point-to-point passenger transport system is currently undergoing its 8th design iteration. The primary change at this stage is a smaller wing with a higher angle of attack trim range capability to enable skip trajectories over large landmasses. These shall avoid sonic boom disturbances on the ground. In this study, selected SpaceLiner 8 and SpaceLiner 7 P2P trajectories are compared regarding flight profile, sonic boom and population response estimation. The SpaceLiner 8 demonstrates lower population disturbances as well as lower peak heat fluxes showing the promising current design.

1. Introduction

The aerodynamic configuration of an airborne vehicle directly impacts its flying characteristics and as a consequence the feasibility of the mission scenario. The DLR concept vehicle SpaceLiner is a vehicle vision that is capable of both orbital spaceflight and point-to-point passenger transport on Earth. For the latter, it is crucial to identify suitable connections between key economic centres of the world. While the actual demand for a realized vehicle remains uncertain, the research into these systems demands thorough analyses of the potential flightpaths already at an early stage in the development. Compared to current civil aviation, super- and hypersonic trajectories pose additional noise disturbances on the general population due to the vertical rocket launch but mainly because of the sonic boom created by the supersonic flight.

Once the overall geometric features of the vehicle are specified, the sonic boom characteristics are more or less defined. The sonic boom disturbance on the current SpaceLiner version 7 was identified as a critical issue and led to the key requirement of the currently investigated version 8. Instead of just following a gliding re-entry trajectory with a large sonic boom carpet on the ground, the SpaceLiner 8 shall also be able to ascend out of the atmosphere to ‘skip’ over certain areas and by that avoid any noise disruption on the ground. This new wing was found in an aerodynamic shape optimization. The new vehicle allows higher trimmable angles of attack to enable re-entering the atmosphere at low heat fluxes.

In order to validate the new aeroshape and demonstrate its advantages compared to the old version, the goal of this study is to compare the flight characteristics of the two vehicles by examining actual reference point-to-point trajectories. This is performed with the same multi-objective optimization routine using evolutionary algorithms that has been used before for SpaceLiner 7 trajectories [1]. Additionally, the expected sonic boom and its resulting impact on the general population will be analysed and compared between the two vehicles.

2. Vehicle description

The SpaceLiner (see Figure 1) is a rocket-powered two-stage fully-reusable vehicle that shall be operated as a point-to-point passenger transport system as well as an orbital launcher [2]. It enables high-speed travel between continents and could connect for example Europe with Australia with a flight time of about 90 minutes. It is powered by LOX/LH2 full-flow staged combustion cycle engines in both stages. The vehicle takes-off vertically from a launch pad and both stages land horizontally on a runway. During the first stage ascent, all engines on the vehicle are active with a crossfeed system supplying propellant to the second stage engines. After booster separation, the second stage accelerates the

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vehicle towards its target destination, which is, depending on the configuration, either a spaceport on Earth or an orbit. The passenger stage performs a horizontal landing at the destination spaceport.

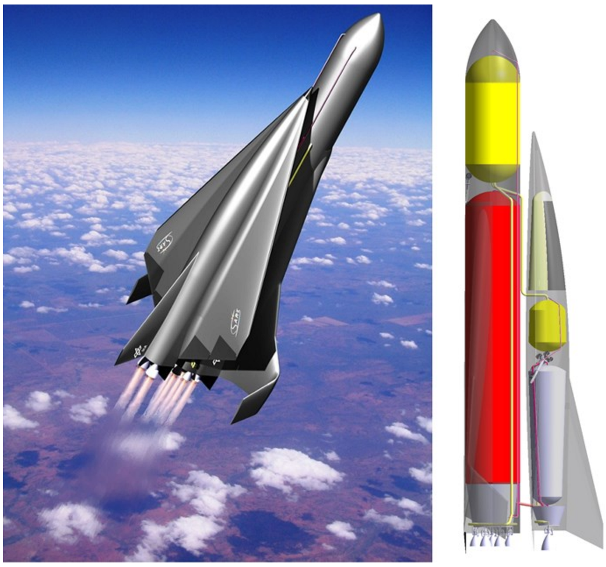

Figure 1: Render of the DLR SpaceLiner 7 ascent (left)
and the detailed configuration vertical on the launch pad (right)

What happens between the end of the rocket-powered ascent and the horizontal landing is a current point of investigation going from SpaceLiner version 7 to version 8.
SpaceLiner 7 was mostly optimized for a high lift-to-drag ratio at hypersonic speeds [3][4]. This resulted in a purely gliding flight capability with trimability up to 20° angle of attack. The flights of the SpaceLiner 7 (SLP7) stay within the atmosphere and generally produce a sonic boom along the whole trajectory [5]. As a result, many people would experience sonic booms on a regular basis if such a system would be in regular operation. While some of the sonic booms created while flying at high altitudes only have low overpressures and by that a lower noise impact and fewer disturbed people, the creation of a sonic boom over populated areas should be avoided at all if possible.
This is why the SpaceLiner 8 (SLP8) shall be able to skip over populated landmasses by ascending outside of the atmosphere in addition to a good atmospheric gliding performance at high altitudes. When re-entering the atmosphere, such a vehicle requires trimability to higher angles of attack to, among others, reduce the peak heat flux on the vehicle. The result of this optimization was a smaller wing (see Figure 2) creating a compromise between good lift-to-drag ratio and trimability for re-entry [6][7]. Additionally, the smaller wing led to a lower estimated wing mass, which in turn increased the overall delta-v available for the system. While more aspects of the vehicle are under investigation for the new version, for this study the key aerodynamic difference between the passenger stages of the SpaceLiner 7 and SpaceLiner 8 is the wing and its trim capability.

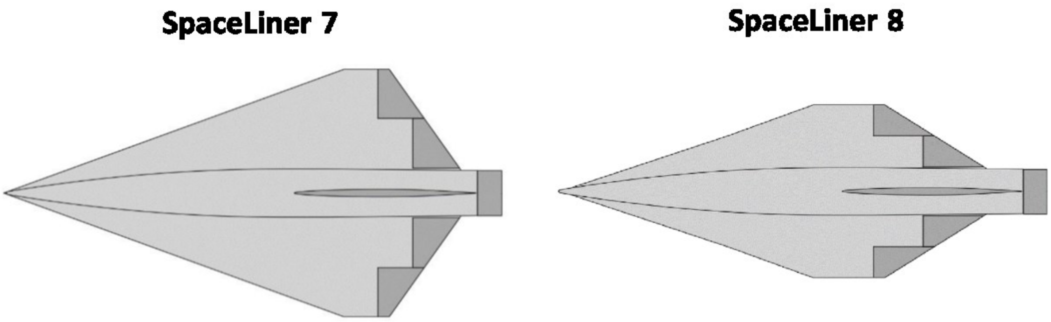

Figure 2: Wing geometry of SpaceLiner 7 (left) and SpaceLiner 8 candidate (right) [7]

Apart from the wing transformation, there are additional investigations and changes proposed for the SpaceLiner 8. Most notably, the cabin housing the passengers was found to be aerodynamically unstable. An investigation on adding small wings has identified promising solutions, however no final configuration has been defined [8]. While this could have additional ramifications for the aerodynamic performance, these changes have not been implemented for this study.

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3. Methodology

To compare the two vehicle iterations, this study consists of two parts: First, the point-to-point trajectory optimization and second, the sonic boom and population disturbance analysis. The trajectory optimization identifies feasible routes between the launch and landing sites and provides the flight profile (e.g. altitude over time) for the analysis. Because the sonic boom is not calculated directly during the trajectory optimization due to its high computational effort, it is analysed in a second step. The detailed methodologies utilized in this study have been described in journal papers before [1][5]. An overview of the methods is given here but the primary focus of this paper shall be their utilization for the vehicle comparison.

3.1 Trajectory optimization

Finding a suitable trajectory for such a vehicle is challenging and complex as the flight profile must arrive at the destination, balance the loads on the vehicle and also avoid overflying the population on the ground as much as possible. The trajectories of the SpaceLiner are optimized in a single procedure from launch to arrival in the landing zone at an altitude of 20 km. The terminal area energy management of finding the optimal glide path to land on a runway is specific to the local conditions and is not part of the optimization. Instead, the vehicle must arrive within a constrained area surrounding the spaceport with sufficient energy left to comfortably reach the runway.
The optimization is performed with a multi-objective optimizer utilizing evolutionary algorithms [9][10]. It exploits natural evolution processes by evolving a set of solutions over a number of generations and adapting the best solutions with for example mutation and crossover processes. A diverse solution space is explored to find a suitable trade-off between the two primary objectives: Minimizing peak heat flux and overall population disturbance. With this combination, trajectories are found that limit the critical thermal loads on the vehicle while also reducing the disturbance on the general population.
While the peak heat flux is directly derived from the flight data, the population disturbance along the flightpath is determined by using a global population density database called GPWv4 [11]. The overflown population is summed up along 5-km steps along the whole trajectory as long as the vehicle flies lower than 80 km in altitude where a sonic boom is expected to reach ground level. The final sum of the population is minimized by the optimizer. Because the actual sonic boom reaches the ground not only below the vehicle but also spreads laterally, the GPWv4 database is adapted to show worst-case values in a radius of about 200 km. As a consequence, the optimizer is inclined to find routes sufficiently far away from the actual population – for example navigating around a coastline by staying at least 200 km away.
During the rocket-powered ascent, the variable parameters are the launch azimuth, pitching rate, thrust vector control, burn time and angle of attack of the second stage. During the unpowered descent, the angle of attack and bank angle is varied across fixed timesteps.
Summarizing, the trajectory optimization finds suitable routes in a challenging and constrained environment and balances the loads on the vehicle with the real-world impact on the population.

3.1 Sonic boom

A sonic boom is created when the shockwave from a supersonic vehicle reaches the ground and appears as a sharp noise to the observer. The shockwave creates a pressure difference – overpressure – with a fast rise in the beginning. Because it arrives without warning, the sonic boom can lead to startle effects and negatively impact the population's quality of life when occurring regularly. While flying super- or hypersonic, the sonic boom reaches the ground along the whole flight paths and extends laterally until a certain cut-off distance – creating a sonic boom 'carpet' on the ground (see Figure 3 left). The strongest sonic boom overpressure in stationary flight is directly below the vehicle and it decreases laterally. The carpet only extends to a specific distance because the sonic boom rays are bent in the atmosphere and at some distance refract upwards again (see Figure 3 right). While these rays can be bent towards the ground again at a farther lateral distance, the noise has dissipated sufficiently to turn it into a rumbling sound instead of a sharp noise which doesn't create the same disturbance responses. Thus, the computation of the sonic boom carpet in this study focuses on the primary carpet created below the vehicle. [12]
Because of these sonic boom characteristics, civil supersonic flight is facing tough regulatory hurdles, which also applies to hypersonic vehicles. Acceptance within the impacted population is critical for the realization of such a project. As a reference: The Concorde created a sonic boom of about 92 Pa at 16 km altitude and Mach 2 and was prohibited to fly over land in its operating countries. Therefore, these issues must be investigated already in the early stages of the design process.
For this study, the sonic boom is estimated based on a simplified sonic boom prediction methodology that is one of the standard tools within the community [13]. Based on the vehicle geometry and flight point characteristics (Mach

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number, altitude, angle of attack and flight-path angle), the program calculates the maximum overpressure and lateral extension as well as the boom duration. Additionally, the overpressure decrease towards the lateral edge can be computed. Knowing the overpressure and the lateral extension, a sonic boom 'carpet' is calculated along the flight trajectory. Using historical sonic boom population survey studies, which correlate the overpressure with the potential disturbed fraction within the population, the expected disturbance on the ground is computed with the GPWv4 population density database. The final result is an estimation of how many people are expected to be annoyed when assuming regular operations of one or more overflights per day.

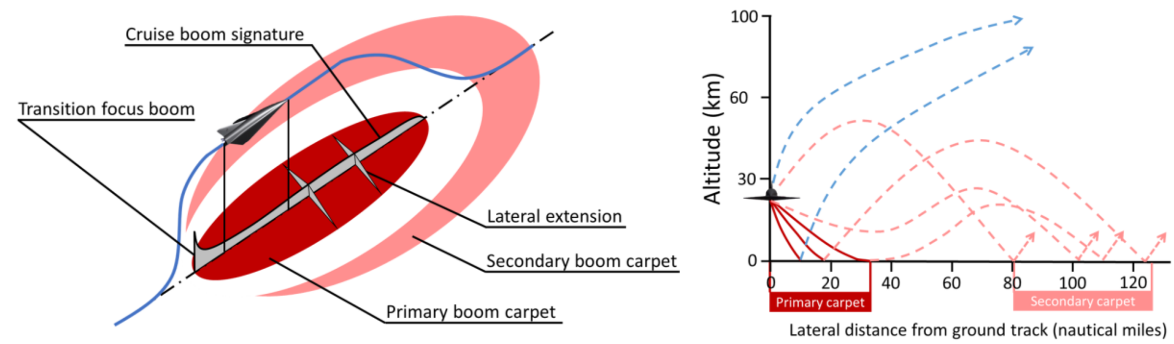

Figure 3: Sonic boom propagation overview (left) and lateral atmospheric effects (right), adapted from [12]

4. Results

The primary focus of the study is to compare the impact of the aerodynamic shape change from SLP7 to SLP8 on the flight profile and the sonic boom. First, the sonic boom characteristics of both vehicles are investigated in a parametric analysis. Afterwards, the flight profile and detailed sonic boom is analyzed for a few selected routes that were optimized with both vehicles. Finally, the population disturbance is evaluated.

4.1 Sonic boom characteristics

The sonic boom reaching the ground is predominantly determined by the geometric shape and the flight profile. While the model used in this study is only low fidelity, differences can still be identified.

Figure 4 shows the sonic boom overpressure results of a parametric study comparing the two vehicles at different Mach numbers and altitudes at a constant flight-path angle of 0°. The altitude was chosen based on a typical gliding re-entry profile. The image on the left shows the absolute overpressure values over angle of attack (AoA). Because of their different trim ranges, the SLP7 is only shown up to an angle of attack of 20°, while the SLP8 is shown up to 36° if the program converged at those AoA. The figure on the right shows the relative change of SLP8 compared to the SLP7 baseline which is held constant at the value of 100. It only shows the change up to 20° AoA.

Overall, the sonic boom overpressures for the two geometries are quite close together which is reasonable given that only the wing geometry has changed but not the overall dimensions. For the hypersonic Mach numbers, the pattern is similar with higher overpressures in the low AoAs and lower overpressures for the SLP8 at higher AoAs. In contrast, the investigated supersonic Mach numbers have higher overpressure values across the board for SLP8 – with relative changes up to 15%.

In terms of absolute values, the overpressure increases with lower Mach numbers and altitude as expected. At Mach 20 and 65 km, the overpressure barely exceeds 10 Pa. Compared to that, it increases to values between 60 and 100 Pa at Mach 1.5 at 25 km altitude and AoA up to 20°. For the SLP8, the higher trim angles beyond 20° lead to an overpressure of at maximum 170 Pa.

The program has the limitation that the so-called vehicle shape factor K_S is calculated by using the tool HOTSOSE which is utilizing local surface inclination methods to determine the lift of the vehicle. However, these methods are generally valid for the hypersonic range and the assumptions made in these methods become less accurate with decreasing Mach numbers. This should be kept in mind when looking at the Mach numbers 2 and 1.5.

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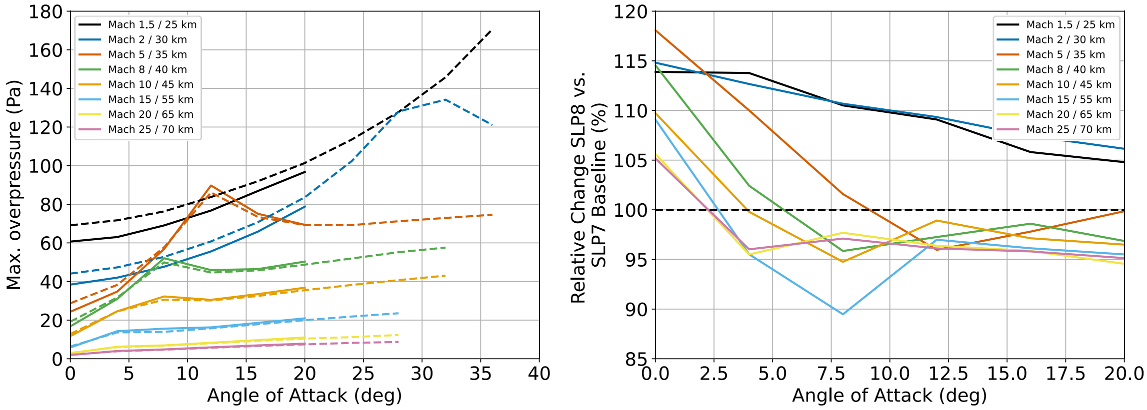

Figure 4: Parametric comparison of sonic boom overpressure over angle of attack between SpaceLiner 7 (solid lines) and SpaceLiner 8 (dashed lines) at different Mach numbers and altitudes.
Absolute values (left) and relative change compared to SLP7 baseline (right)

4.2 Flight analysis

In this chapter, the flight difference between SLP7 and SLP8 is analyzed for a set of feasible routes. These will be the reference trajectory from Australia to Scotland and back. Additionally, the route Florida – India showcases a perfect example of the SLP8 capabilities and how it can play out it benefits.

4.2.1 Australia – Scotland

Australia to Europe is one of the classic reference routes for the SpaceLiner as it represents one of the longest possible flights. In this case, Scotland is chosen as the launch site within Europe due to its broad access to high inclination trajectories, while still being close to a large population in central Europe. Figure 5 shows the trajectories on a world map with their associated estimated sonic boom. Both vehicles fly approximately the same route with a northbound launch over the Pacific and crossing over to Europe via the Arctic polar region. The SLP7 flies a slightly more northern route going almost directly over the North pole. While the SLP7 has a sonic boom during the whole descent flight, the SLP8's boom only starts in the northern Pacific as it performs a small skip above 80 km to avoid noise disturbance over the Oceanic countries.
This skip can also be seen in the flight profile shown in Figure 6. In the beginning of the descent flight, the SLP8 stays above 80 km for about 4000 km. Afterwards, it enters a gliding flight similar to the SLP7 but at a higher altitude. However, due to the worse gliding performance of the SLP8, it flies with a steeper flight-path angle (FPA). Afterwards, the profile of the two vehicles over time and also over flight distance is similar.
The aerodynamic shape difference can also be seen in the altitude-velocity diagram where the SLP8 line is shifted upwards compared to SLP7. This means that for a given altitude, the SLP8 flies at a lower velocity. Consequently, it also flies at a lower dynamic pressure. The key result from these effects can be seen in the stagnation point heat flux (SPHF) diagram which is substantially different between the two vehicles. With a peak SPHF of about 850 kW/m² based on a reference nose radius of 0.2 m, the SLP8's value is about 40 percent lower than SLP7. Consequently, the integrated heat load of the SLP8 will also be substantially lower. This will reduce the performance requirements for the thermal protection system considerably.
The sonic boom profile over time is mostly similar for the two vehicles. As stated above, the sonic boom of the SLP8 is zero in the first 600 seconds of the flight while it performs the skipping manoeuvre. In this phase, the SLP7 has a small sonic boom, which will only disturb a very small fraction of the population. In the subsequent gliding phase above 50 km altitude, the SLP8 sonic boom is about double of the SLP7 while still remaining at low absolute values below 30 Pa. This is a consequence of the steeper FPA combined with higher flown AoAs. In the final flight phase below 50 km, the sonic boom follows a similar pattern for both increasing to over 100 Pa. The detailed course depends on the specific approach to the landing site.

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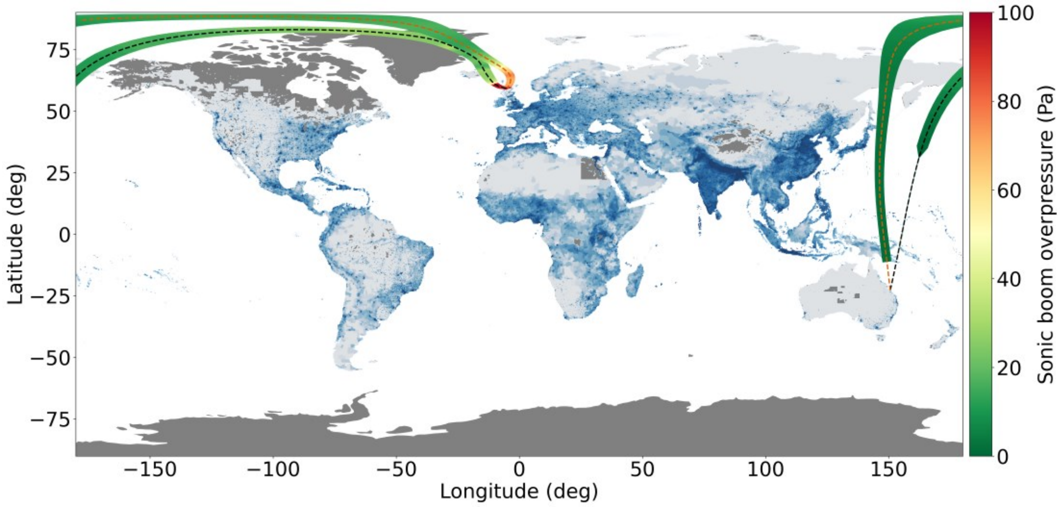

Figure 5: World map of the route Australia – Scotland with SpaceLiner 7 (orange dashed line) and SpaceLiner 8 (black dashed line), and their sonic boom overpressures (normalized between 0 and 100 Pa)

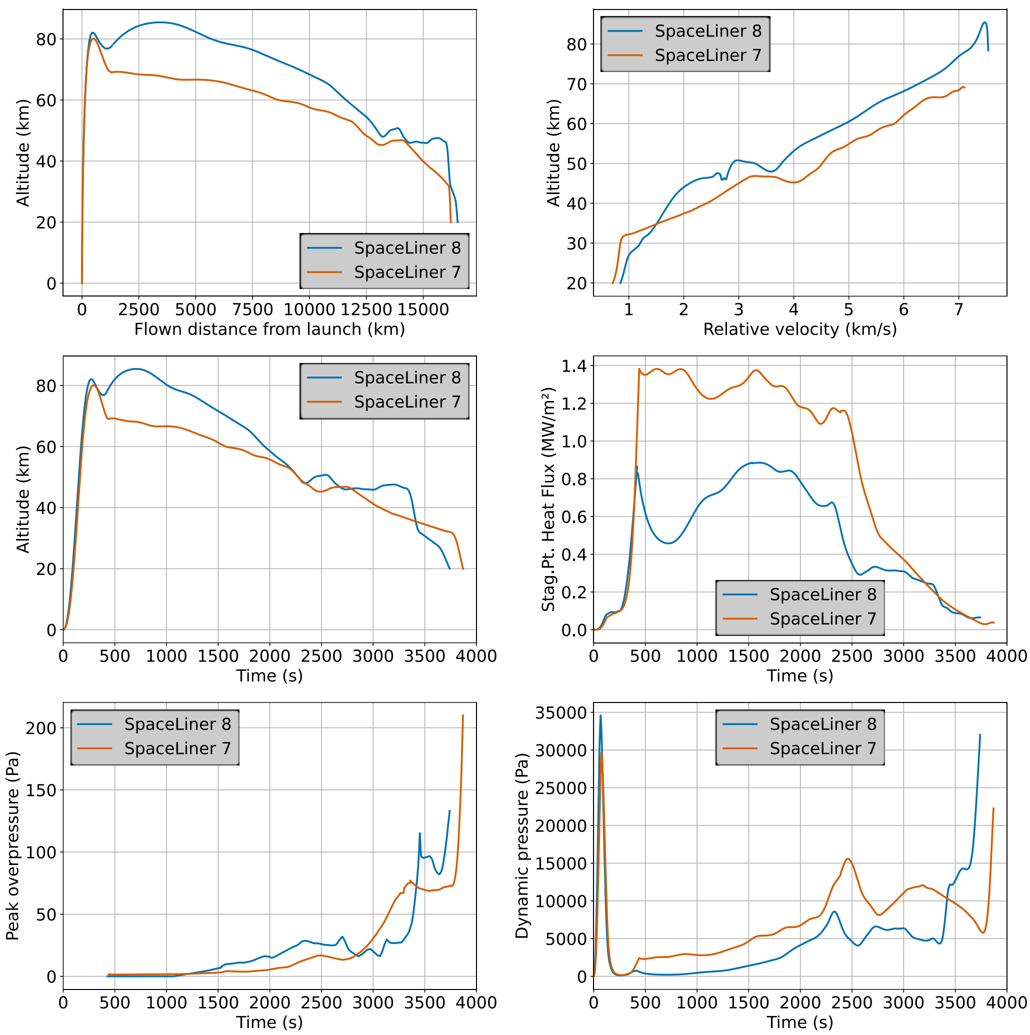

Figure 6: Flight profile comparison on the route Australia – Scotland

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4.2.2 Scotland – Australia

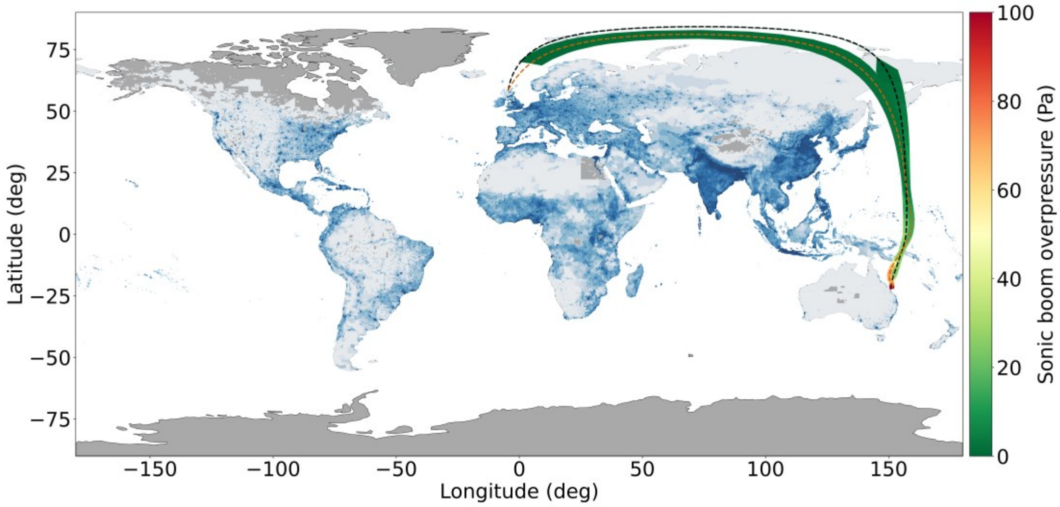

Figure 7: World map of the route Scotland – Australia with SpaceLiner 7 (orange dashed line) and SpaceLiner 8 (black dashed line), and their sonic boom overpressures (normalized between 0 and 100 Pa)

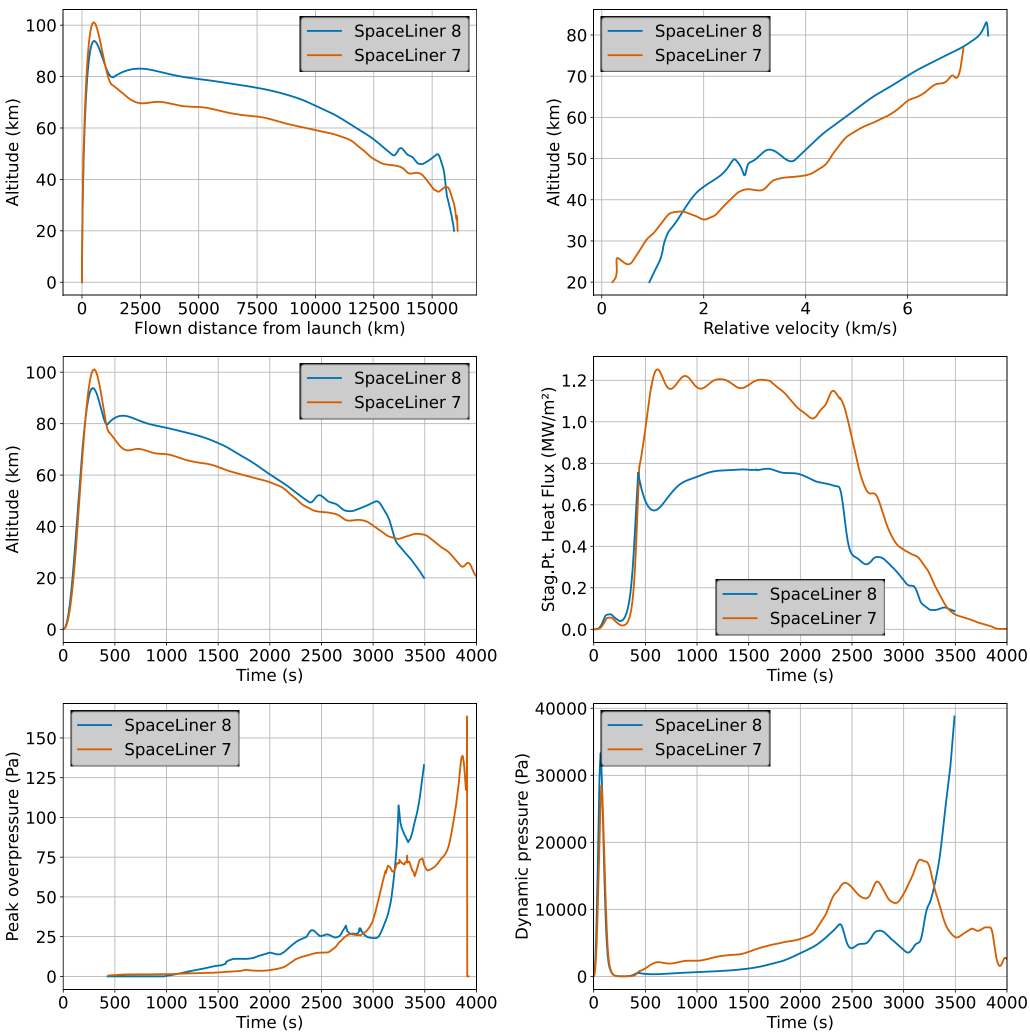

Figure 8: Flight profile comparison on the route Scotland – Australia

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Figure 7 shows the trajectory map of the second investigated flight route: Scotland – Australia. This is the reverse flight of the reference case. Overall, the flightpaths are very similar: Both launch towards the Arctic and then glide towards Australia over the Pacific. Again, the SLP8 performs a skipping manoeuvre in the first part of the descent flight. Because of the distorted Mercator projection in Figure 7, this appears a lot longer than it actually is with a skip distance of about 2000-3000 km. The flight profile can also be seen in Figure 8.
As was the case before, the SLP8 flies at higher altitudes and a steeper FPA as long as both vehicles are above 50 km. Afterwards, the flight path is similar depending on the actual arrival at the destination. Analysing the altitude over velocity and the SPHF, the flight characteristics are quite similar compared to the previous flight. SpaceLiner 8 flies at higher altitudes for a given speed (or a lower speed for the same altitude) and the peak SPHF is approximately 35% lower than for SLP7.
The sonic boom overpressure also follows a similar pattern. As long as the vehicles are above 50 km in altitude, the overpressure remains below 30 Pa. In this phase, the SLP8 has a higher overpressure than SLP7 due to the same reasons of steeper FPAs and higher AoAs. Towards the end of the flight, the overpressure increases steeply to above 100 Pa.

4.2.3 Florida – India

The third flight in this comparison goes from Cape Canaveral in Florida, United States to Satish Dhawan Space Center (SDSC) in India. SDSC currently features launch pads for large rockets and is therefore ideally suited as a SpaceLiner spaceport location. It is located on the east side of India allowing for launches towards the east and south. The route from Florida to India was identified in the past without the possibility of a direct return flight due to the constraining launch azimuths and the worse performance going westward. Instead, it was part of an eastbound chain of flights: Australia to Florida, then Florida to India and then India back to Australia.
In the past, the location in India was not SDSC but a hypothesized location at the southern tip of India. The reason for this was that the SpaceLiner 7 is not capable of flying a curve around India and Sri Lanka over the Ocean towards SDSC. Instead, it has to cross India over land leading to high population disturbances. Even “forcing” the optimizer to take a more southern route has not yielded any converging results with sufficiently low SPHFs. Consequently, the comparison shown in Figure 9 must be observed with the fact that SDSC is a suboptimal landing site for SL7 and, as will be seen, a perfect site for SLP8.
The flight routes displayed in Figure 9 take distinctly different paths. While the SLP7 has to take the direct route over central Africa, the SLP8 performs a large skip over the Caribbean and South America to then glide over the Atlantic and Indian Ocean. Because of this large skip, the sonic boom only reaches the ground south of Africa and there is no larger landmass that is hit by the sonic boom. In contrast, the SLP7 sonic boom reaches the ground all over Africa and also in India in the final part of the flight.
The large difference in the flight characteristics can also be seen in the flight profile overview in Figure 10. While the SLP7 starts its gliding flight at its typical altitude below 80 km, the SpaceLiner 8 ascent goes to over 150 km in altitude. It then stays above 80 km for about 8000-9000 km avoiding any sonic boom in this area, allowing the vehicle to fly over very populated parts of the Caribbean and South America. After re-entering the atmosphere, the SLP8 follows a gliding flight pattern until its destination. The different route leads to an overall flown distance of 24,000 km compared to only 17,500 km for SLP7. 24,000 km is the largest observed distance of any investigated trajectory so far. In the gliding phase, the vehicle comparison shows similar behaviour as before. The SLP8 flies at a higher altitude for a given velocity until about 50 km and the peak SPHF is about 25 percent lower.
The sonic boom of the SLP8 stays at zero for a long time. During re-entry from the higher atmosphere, there is a short timespan with a sonic boom as it moves below 80 km. However, it performs another little skip leading to another phase of zero overpressure on the ground. Once the vehicle is properly in its gliding phase, the overpressure then increases gradually to 30 Pa at 50 km altitude. Afterwards, the overpressure increases more significantly to values over 100 Pa. In contrast, the SLP7 has a gradual overpressure increase from the start of the flight, with a similar stronger increase below 50 km altitude.

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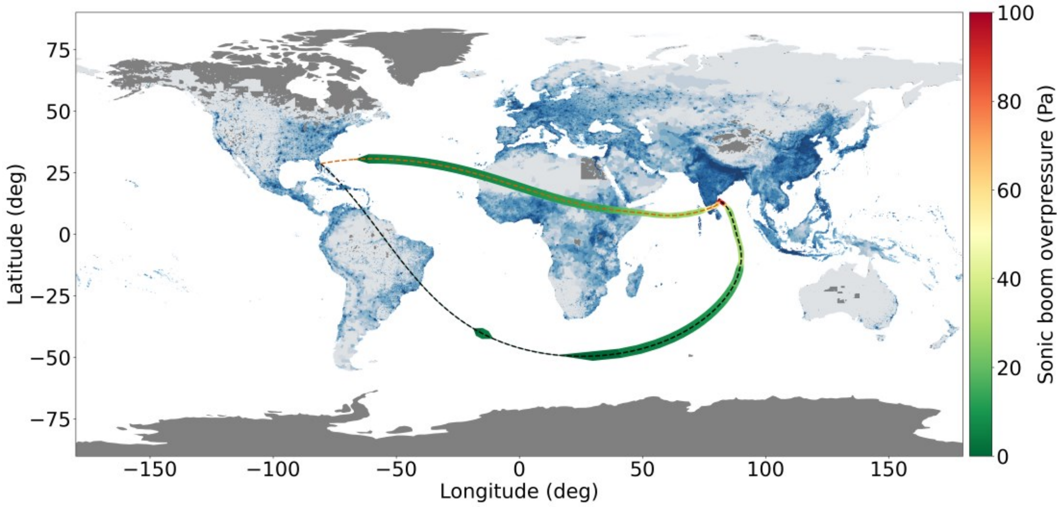

Figure 9: World map of the route Florida – India with SpaceLiner 7 (orange dashed line) and SpaceLiner 8 (black dashed line), and their sonic boom overpressures (normalized between 0 and 100 Pa)

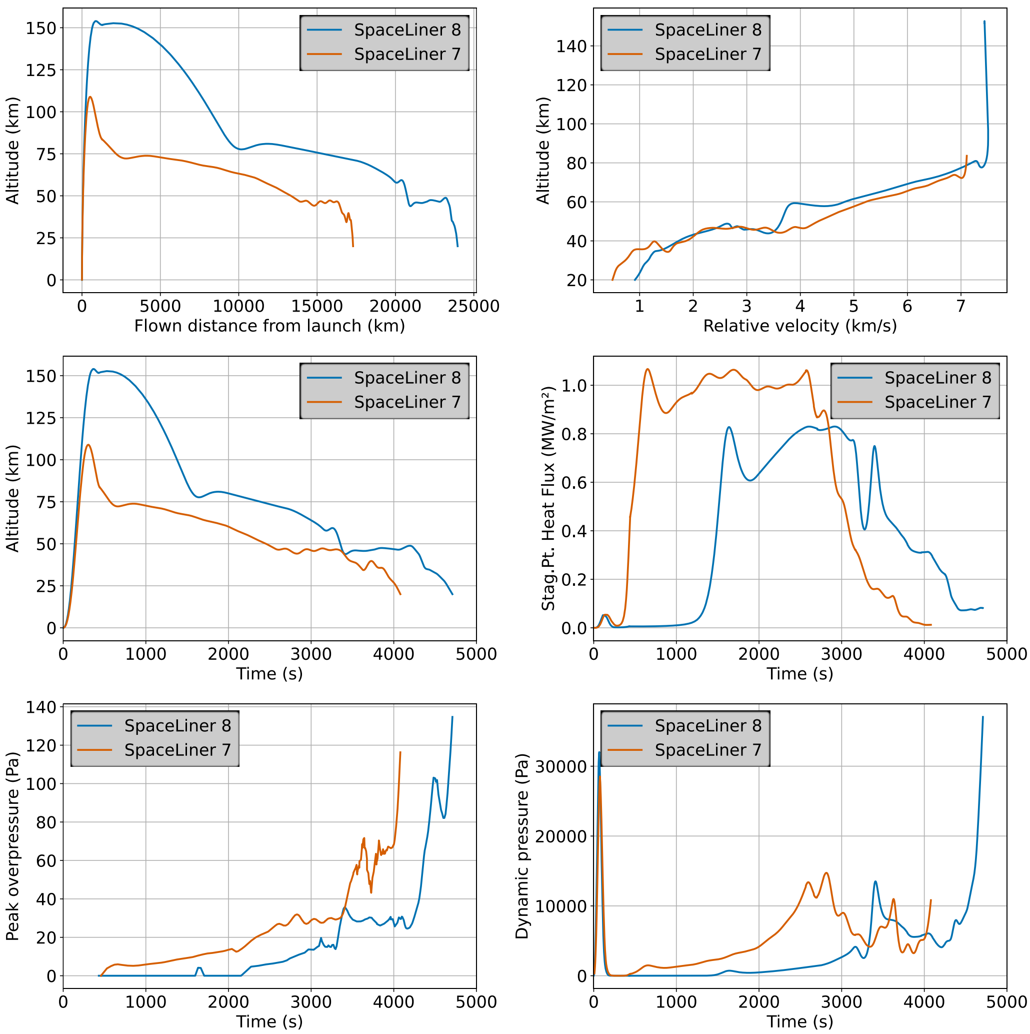

Figure 10: Flight profile comparison on the route Florida - India

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4.3 Population response

The sonic boom impact on the general population is a critical aspect when investigating such inter-continental high-speed trajectories. The expected population disturbance is computed by combining the sonic boom carpet with the overflown population and calculate from that the share of disturbed people. The latter is done with population survey studies correlating the overpressure with share of disturbed population. In this study, the correlation created by the American National Standards Institute (ANSI) is used which has been show to paint the most realistic picture [5].
Figure 11 displays the impacted sonic boom area for all three investigated flight routes as a comparison between SpaceLiner 7 and SpaceLiner 8 and sorted by overpressure magnitude levels. Because of the skipping maneuver performed by the SLP8, even if it is a small one, there is a prominent difference between the two vehicles. On average, there is a difference of about 1.5 million km² between the SLP7 and SLP8 route. While the SLP7's sonic boom results in total impacted areas between 4.5 and 5 million km², the SLP8 impacts a smaller area between 3 and 3.5 million km² for the same routes. This is especially noteworthy for the Florida – India route where the SLP8 flown distance is about 35 percent or 6500 km higher yet the impacted area is still lower due to the very long high arc flown over South America.
The large difference in this route especially can also be seen looking at the total number of people experiencing the sonic boom (or 'overflown people') shown in Figure 12. While the SLP7 flies over 130 million people, of which about 14 million will be disturbed, the SLP8 flies over zero. While this difference is astounding, keep in mind that the landing site in India is a bad location for the SLP7 as it cannot fly around Sri Lanka to the eastern coast. In an analysis in the past with a hypothesized landing site at the southern tip of India, the SLP7 'only' overflew about 80 million people with a disturbance expectation of 500k people. So, the last part of the flight over the landmass makes an enormous difference.
For Australia to Scotland the number of overflown people decreases by over one magnitude from 1.7 million to about 60k. However, because most of these people in the SLP7 flight were only impacted by a very small overpressure, the share of disturbed people only decreases from about 6000 to 2000. This can also be seen in Figure 13 where basically all disturbed people are experiencing booms smaller than 20 Pa for SLP7, while the SLP8 also flies over people with 20 to 50 Pa overpressure. The latter indicates that the final approach of the SLP8 has not been optimized as well as possible because the SLP7 managed to find a route around Iceland and the Faroe Islands without impacting any people there.
The situation is different for the reverse direction Scotland – Australia. Because basically no one lives in the area overflown in the first half of the flight – the Arctic – the difference in overflown and disturbed population is small between SLP7 and SLP8. In fact, there is an increase in overflown people from 500k to 700k with a disturbed share increase from 32k to 35k – an approximately 10 percent increase. The SLP8 experiences higher overpressures in the gliding phase between 75 and 50 km altitude which might be one of the reasons for the higher disturbance in this case. This might be improved upon by optimizing the final part of the flight. Currently, the SpaceLiner 8 is arriving at the landing location quite fast and for the sonic boom overpressure increase towards the end of the flight a high-altitude transition from supersonic to subsonic is beneficial.

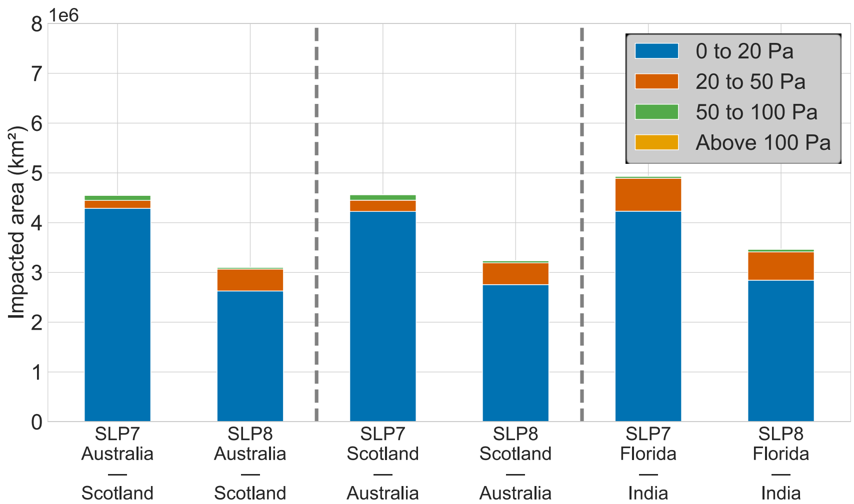

Figure 11: Sonic boom impacted area comparison between SLP7 and SLP8 routes

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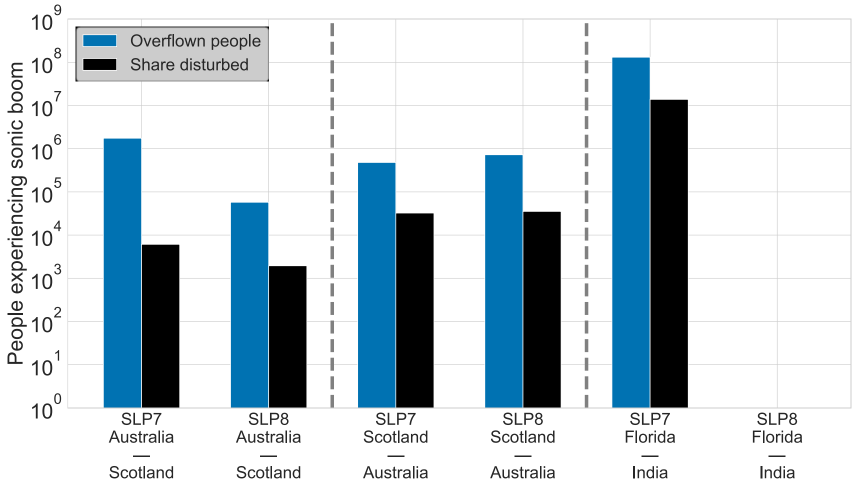

Figure 12: Sonic boom overflown people and share disturbed comparison between SLP7 and SLP8 routes

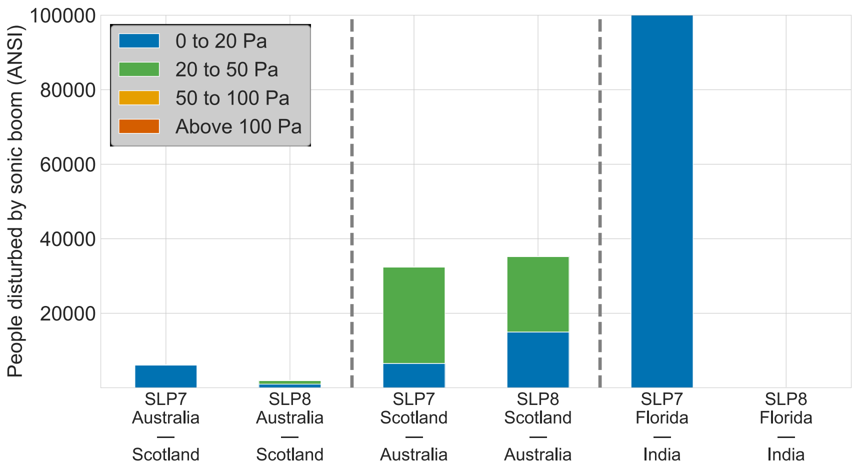

Figure 13: Sonic boom disturbed population comparison between SLP7 and SLP8 routes

5. Discussion

This comparison between the SpaceLiner 7 and SpaceLiner 8 trajectories based on actual possible flight routes between two points on Earth yielded some interesting results. The primary takeaway of this study is that the larger range of trimmable angle of attacks of the SLP8 vehicle at the expense of a lower lift-to-drag ratio at hypersonic speeds leads to more flexible trajectory planning and optimization. Compared to SLP7, it is not only bound to purely gliding re-entry trajectories but is also capable of 'skipping' over for example very populated land masses in the first 5000-10000 km of the flight.

This capability already showed promising results for the reference route Australia – Scotland, where some countries in the Pacific Ocean could be skipped and the number of disturbed people decreased by about two-thirds. Then, it demonstrated its powerful impact for the route Florida – India by choosing a completely different route and instead of going over Africa, the vehicle skips over the Caribbean and South America completely and reduces the number of overflown and disturbed people to zero.

In contrast, this capability benefit did not play out for the reverse reference case from Scotland to Australia. Because the largest share of overflown population lives in the second half of the flight, where both vehicles are in a gliding flight, the SLP8 is not capable of reducing the number of disturbed people on the ground. It appears that the SLP8 generally experiences higher overpressures between 75 and 50 km in altitude because of the steeper flight-path angle and higher flown angles of attack.

Looking at these difference, there is a trade-off to be made when choosing between the SLP7 and SLP8 configuration. Is it better to be forced to fly over large populated areas creating only a small overpressure, or to use the capability advantage of skipping over large distances at the expense of higher overpressures in the latter part of the flight? This

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depends on the specific flight route and cannot be generalized. While Australia-Scotland and Florida-India benefit from the skipping trajectory, Scotland-Australia does not.
These results also encourage more route optimizations to identify the impact of the new vehicle design but also to investigate potential new spaceport locations, which might have not worked with the SLP7 due to their proximity to populated landmasses which needed to be flown over in the beginning of the flight.
Another major takeaway of these investigations is that the new vehicle can effectively reduce the peak stagnation point heat flux and the overall integrated heat load for all investigated routes when compared to SLP7. This will reduce the requirements on the thermal protection system as some of the very high temperature peaks on the leading edges can be decreased.
One more idea for future investigations is the introduction of a re-ignitable engine. If there is remaining propellant in the vehicle, the vehicle could increase the altitude in the latter parts of the flight to reduce the sonic boom impact on areas that are unavoidable like the Pacific island countries on the route Scotland – Australia.
The sonic boom calculation currently delivers satisfactory results based on the simplified prediction methodology by Carlson. However, for future investigations it could be beneficial to combine Carlson for the peak overpressure computation with ray tracing for the carpet properties as a 'medium-fidelity' solution as suggested in [14].

6. Conclusion

The investigation of the sonic boom impact is a central part of the SpaceLiner development process as it has a tremendous influence on the feasibility of real-world operations. The SpaceLiner 8 development was started with the goal of enabling skipping trajectories after the high sonic boom impact found on some SpaceLiner 7 trajectories.
After the aerodynamic design of the new wing, this study is validating the design change for the actual potentially flown trajectories. Compared to the SLP7 trajectories, the newly found routes offer higher versatility and overall less disturbance on the ground. The capability of ascending to high altitudes and flying an arc above the atmosphere can reduce the impact on the ground significantly as long as the overflown population is in the first 5000-10000 km of the flight. This was especially the case for the route Florida to India where the sonic boom disturbance on the ground could be reduced to zero. However, because the SLP8 tends to fly at higher angles of attack and steeper flight-path angles during the gliding re-entry, its sonic boom overpressure also tends to be higher at hypersonic speeds which can be a disadvantage for certain trajectories like Scotland – Australia.
In future work, more innovate routes should be investigated to further validate the system. Additionally, future iterations could also feature for example a re-ignitable engine for flexible altitude increase. Summarizing, this study is a good step in the development roadmap of the SpaceLiner 8 and shows the flight capabilities of the promising new wing configuration.

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