Luton Rising
Our airport.
Our community.
Our planet.

December 2023

London Luton Airport Expansion

Planning Inspectorate Scheme Ref: TR020001

Volume 8 Additional Submissions (Examination)

8.135 Applicant's Post Hearing Submission - Issue Specific Hearing 8 (ISH8)

Infrastructure Planning (Examination Procedure) Rules 2010

Application Document Ref: TR020001/APP/8.135

The Planning Act 2008

The Infrastructure Planning (Examination Procedure) Rules 2010

London Luton Airport Expansion Development Consent Order 202x

8.135 APPLICANT'S POST HEARING SUBMISSION – ISSUE SPECIFIC HEARING 8 (ISH8)

Deadline:	Deadline 6
Planning Inspectorate Scheme Reference:	TR020001
Document Reference:	TR020001/APP/8.135
Author:	Luton Rising

Version	Date	Status of Version
Issue 1	December 2023	Additional Submission – Deadline 6

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1 INTRODUCTION

1.1.1 This document contains Luton Rising's (a trading name of London Luton Airport Limited) (the Applicant) oral summary of evidence and post-hearing comments on submissions made by others at Issue Specific Hearing 8 (ISH8) held on 29 November 2023. Where the comment is a post-hearing comment submitted by the Applicant, this is indicated. The Applicant has also included tabulated responses to each of the action points raised by the Examining Authority (ExA) for ISH8 originally published on 1 December 2023 and republished 5 December 2023 to reflect amended deadlines requested by the Applicant and agreed by the ExA.

1.1.2 This document uses the headings for each item on the agenda published by the ExA on 20 November 2023 for ISH8.

2 AGENDA ITEM 1: WELCOME, INTRODUCTIONS, ARRANGEMENTS FOR THE HEARING

2.1.1 The Applicant, which is promoting a proposal to expand London Luton Airport (the Proposed Development), was represented at ISH8 by Rebecca Clutten and Michael Humphries KC, supported by the following members of Applicant's team:

a. Dr Calum Sharp, Noise and Vibration Lead, Arup.
b. Edward Robinson, Noise and Vibration Modelling Lead, AECOM
c. Louise Congdon, Managing Partner, Need Case Lead, York Aviation
d. Mark Day, Associate, Arup, Green Controlled Growth Lead.
e. Jenny Dunwoody, Health and Communities Lead, Arup
f. James Bellinger, Air Quality Lead, Arup
g. Ian Davies, Greenhouse Gases Lead, AECOM
h. Ben Murray, Climate Change Resilience Lead, AECOM
i. Dr Paul Clack, Biodiversity Lead, Arup
j. Dr James Riley, Biodiversity Air Quality Lead, AECOM
k. Jason Fairbairn, Water Resources Lead, Arup
l. Fida Choudhury, Drainage Lead, AECOM
m. Julian Woolley, Landscape and Visual Lead, Pick Everard
n. Heather Lalupu de Oettle, Senior Engineer, Geotechnics Lead, Arup
o. Marcus Scrafton, Design Lead, AECOM
p. Tom Smith, Planning Statement Lead, AECOM

3 AGENDA ITEM 2: NOISE AND VIBRATION

3.1 Construction noise and vibration

Conclusions regarding piling and night-time construction noise impacts, including any implications for location specific mitigation

3.1.1 The ExA asked if an impact piling noise assessment would be required to ensure that the ExA can reach a conclusion on the likely significant effects of construction.

3.1.2 The Applicant confirmed that restrictions on piling operations had been added to 14.2.7 of the **Code of Construction Practice (CoCP) [REP4-011]** following ISH3 and subsequent discussions with Host Authorities (HAs) and with reference to the New Century Park/Green Horizons Park planning permission.

3.1.3 The Applicant considers that the assessment of construction noise and vibration in **Chapter 16 of the Environmental Statement** (ES) **[REP1-003]** provides a reasonable worst-case assessment within the context of what was likely to occur and therefore provides a robust conclusion on the likely significant effects of construction.

3.1.4 The additional restrictions, noted above, require that no impact piling can occur without an impact piling method statement, including measures to control noise and vibration, being submitted and approved by the local authority as part of the Section 61 (s61) process. This approach to restricting impact piling is recorded as agreed in the Statement of Common Ground (SoCG) for all HAs.

3.1.5 The Applicant confirmed that the s61 consent process is applied in the CoCP to any works that will be noisy or generate perceptible vibration and that it is a well proven process applied on many major infrastructure projects. Paragraph 188 of the National Planning Policy Framework (NPPF) confirms that planning decisions should assume that other enforcement regimes will operate effectively and that this is a standard approach for applications for Development Consent Orders (DCOs).

3.1.6 When asked by the ExA, Luton Borough Council (LBC) and the combined authorities of North Hertfordshire Council, Hertfordshire County Council and Dacorum Borough Council (the Combined Authorities) all confirmed that they were content with the Applicant’s approach in this regard.

3.1.7 The ExA noted that impact piling had been approved in the Green Horizons Park permission and wanted to know that this had been appropriately assessed in the application for development consent.

3.1.8 **Action point 1: To review the effect of impact piling if it were to occur and whether it needs to be assessed in the Environmental Statement (ES).**

3.1.9 The ExA enquired about the night-time construction noise assessment provided in **[REP4-080]** and whether the receptor locations shown in **Figure 16.4** of the ES **[AS-103]** were the receptors used for this assessment.

3.1.10 The Applicant confirmed that Address Base data was used for night time construction noise assessment which includes all buildings within the study area rather than smaller number of receptors shown in Figure 16.4.

3.1.11 **Action point 2: Clarification of why ML15 monitoring data should be applied to all receptors in the night-time noise assessment, rather than ML16 data. Explain how use of ML16 data would affect the results of the assessment.**

3.1.12 The ExA noted that the assessment in **[REP4-080]** identified exceedances of the construction noise LOAEL near M1 Junction 10 and queried whether this triggers the need to identify location specific mitigation.

3.1.13 The Applicant confirmed that no likely significant effects had been identified for the properties exposed above the LOAEL, however the controls required in the CoCP identified that best practicable means would be applied, and noise would be reduced as far as reasonably practicable in line with the policy aims of the Noise Policy Statement for England[1]. If location specific mitigation (e.g. hoarding, selection of quiet equipment, equipment enclosures) were required this would be confirmed through prior approval with the local authorities as part of the s61 process.

3.1.14 The Combined Authorities, CBC and LBC confirmed they were content with this approach to night-time construction noise.

3.2 Surface access noise

Applicant to update on the implications of the new compensation policies for surface access noise receptors, including scope of eligibility and any implications for Crawley Green Road and Stony Lane receptors

3.2.1 The ExA asked for an update on the compensation policies for ground noise and surface access noise in **Draft Compensation Policies, Measures and Community First [REP4-042]**.

3.2.2 The Applicant confirmed that the compensation policy for surface access noise is not new and has been part of the proposals since submission of the application (see first submission version at **[APP-226]**).

3.2.3 The policy has been updated to remove reference to monitoring being undertaken as part of the Transport Related Impacts Monitoring and Mitigation Approach (TRIMMA). The necessary monitoring is now secured purely through the compensation policy via the section 106 agreement. The reason for not undertaking this monitoring as part of the TRIMMA is that the type of monitoring required to determine eligibility is different to the monitoring regime and process set out in the TRIMMA.

3.2.4 The surface access noise compensation policy has also been updated to specify that night-time traffic monitoring is undertaken to allow Transport Research Laboratory (TRL) Method 1 to be used, following discussion at ISH3 and in particular in response to ISH3 Action 16 (see action point in **[EV8-008]** and Applicant response in **[REP4-070]**).

3.2.5 The Applicant clarified that this is not a change to the eligibility criteria, it is just a change to the monitoring approach, and is therefore not expected to change the eligible properties (55 properties on Crawley Green Road between Vauxhall Way and Hedley Rise, see paragraph 16.9.232 of **Chapter 16 of the ES [REP1-003]**).

3.2.6 In response to a query about whether the properties in Stony Lane would be eligible for compensation, the Applicant confirmed that they are not.

3.2.7 The exposure of these properties is between LOAEL and SOAEL (about 5dB below SOAEL) so absolute noise effects in noise policy terms are not significant, and the policy requirement is to mitigate and minimise (not avoid) adverse effects, in the context of sustainable development.

3.2.8 The average increase during the day is an intensification (increase in the frequency) of traffic from about 1 car passby per minute to about 2 car passbys per minute, rather than closer or louder cars.

3.2.9 At this noise exposure below SOAEL, internal noise levels without noise insulation would be expected to be below recommended internal ambient noise levels from BS8233[2] and provision of further noise insulation would not therefore improve the living conditions in the properties.

3.2.10 As set out in **Chapter 16** of the **ES [REP1-003]** no practicable noise mitigation has been identified for receptors on Stony Lane (noise barriers on this stretch of road are not feasible due to engineering constraints and traffic speeds are too low for a low noise road surface to be particularly effective).

3.2.11 The ExA queried whether, with review of traffic numbers and traffic noise being carried out on a five yearly basis, there could be a potential for noise creep in relation to the baseline.

3.2.12 The Applicant confirmed that monitoring and re assessment would be in comparison to Do Minimum (the situation without the Proposed Development and the resulting increase in traffic). This follows the approach used for the assessment carried out in the ES and would not be affected by baseline creep.

3.2.13 When queried, the various local authorities noted they had no issues to raise on the approach to the surface access noise assessment or mitigation, but queried whether there were any figures showing noise insulation eligibility for ground noise.

3.2.14 **Action point 3: In post hearing note, provide reference to noise contour figures that explain eligibility for traffic and ground noise insulation, which would exclude the need to give a list of eligible properties.**

3.3 Fixed plant noise

The revisions to the proposed fixed plant noise management plan and the Hertfordshire Host Authorities' comments regarding fixing noise levels

3.3.1 The ExA queried the proposed monitoring delay of up to one year after notification under Article 44 of the **Draft DCO [REP5-003]** and the logic of this approach and the potential for ambient noise levels increase.

3.3.2 The Applicant confirmed it is a 12-month deadline (not a delay) for practical reasons to allow for required surveys to be carried out following the trigger of the Article 44 notice. The threshold has been reduced to -10dB as noted in response to WQ DCO.1.17 **[REP4-057]** and there should be no interaction with background sound level. Also, the monitoring uses the L_{A90} metric to measure fixed plant noise which measures ambient noise and is insensitive to transient noise such as air noise and road noise.

3.3.3 The LPAs confirmed that they were satisfied with the approach taken on fixed plant noise.

3.4 Aviation noise

Appropriate baseline year for comparisons – Applicant to provide an update on the appropriate baseline/ baseline year for comparisons following the decision to approve application ref: 21/00031/VARCON

3.4.1 The Applicant was asked to provide a brief update on its view of the appropriate baseline following the decision to approve the "P19" 19 mppa planning application (21/00031/VARCON).

3.4.2 The Applicant reiterated that, as set out in **Implications of the P19 Approval for the DCO [REP4-093]**, sensitivity tests were undertaken in the ES to demonstrate that the 18 mppa baseline represents a reasonable worst case compared to 19 mppa.

3.4.3 As discussed at ISH3 (see **Applicant's Post Hearing Submission ISH3 [REP3-050]**), the historic baseline does not factor into assessment of EIA likely significant effects or the identification of significant adverse effects on health and quality of life. This is because firstly, EIA likely significant effects are identified by noise change compared to the future baseline used in the ES that is compliant with both the 2017 consent and P19 consent long-term limits and secondly because the identification of significant adverse effects on health and quality of life is based on exceedance of the relevant SOAEL threshold that is independent of baseline.

3.4.4 As discussed at ISH3, comparisons back to 2019 Consented baseline (the ES sensitivity test) result in the same identification of significant effects on health and quality of life due to exposure above the relevant SOAEL, but a small proportion (night-time only, between 5% and 18%) could be considered 'new' because they would not have been above SOAEL in the 2019 Consented baseline, but these are not residual significant effects on health and quality of life as such effects are avoided by the Noise Insulation Scheme (refer to **[REP4-042]** for detail of the Scheme).

3.4.5 If the Applicant were to repeat this comparison with a P19 compliant baseline, this proportion of 'new' effects would reduce as the P19 consented night-time contour limit is larger than the 2019 consented contour limit based on the 2017 permission. Again, this indicates that the use of a 2019 Consented baseline is a reasonable worst case.

3.4.6 The other way that the 2019 Consented baseline is used in the ES is in Table 3.2 and 3.3 of **Appendix 16.2** of the **ES [REP4-023]** where the Applicant has quantified the proportion of 'sharing the noise benefits' that go to the community with reference to the 2019 Consented baseline.

3.4.7 The tables show the percentage of benefit share that goes to the community will vary over time and depends on the forecast, but ranges from 0 – 68% for the daytime and 0 – 20% for the night-time when measured against the 2019 Consented baseline from the 2017 planning permission.

3.4.8 Undertaking the same quantification using contour area limits from the P19 permission shows a quantified sharing the benefit where a much larger proportion goes to the community: 38 - 82% for the daytime and 0 - 55% for the night-time.

3.4.9 The Applicant's position therefore remains that the worst-case consented baseline was used in the ES sensitivity test and so there is no proposal to update the assessments based on a P19 baseline.

3.4.10 **Post hearing submission:** Updates to Table 3.2 and 3.3 from **Appendix 16.2** of the **ES [REP4-023]** using a P19 compliant baseline are provided here.

Table 3.1 Percentage of noise contour reduction that goes to the community, daytime (based on P19 compliant baseline)

Period	Area of 54dB$L_{Aeq,16h}$ Contour (km^2)				Percentage of noise contour reduction that goes to the community
	Scenario A	Scenario B	Smallest forecast noise contour	Largest forecast noise contour (Noise Envelope Limit)	
Up to 2028	27.4	39.1	29.5	33.6	47 – 82%
2029 – 2033	25.6	39.1	28.2	32.8	47 – 81%
2034 – 2039	23.9	39.1	28.2	30.7	55 – 72%

Period	Area of 54dB$L_{Aeq,16h}$ Contour (km^2)				Percentage of noise contour reduction that goes to the community
	Scenario A	Scenario B	Smallest forecast noise contour	Largest forecast noise contour (Noise Envelope Limit)	
2039 – 2043	22.1	39.1	28.2	32.6	38 – 64%

Table 3.3 Percentage of noise contour reduction that goes to the community, night-time (based on P19 compliant baseline)

Period	Area of 48dB$L_{Aeq,8h}$ Contour (km^2)				Percentage of noise contour reduction that goes to the community
	Scenario A	Scenario B	Smallest forecast noise contour	Largest forecast noise contour (Noise Envelope Limit)	
Up to 2028	34.1	42.9	38.3	44.8	0 - 52%
2029 – 2033	31.8	42.9	36.8	42.8	1 - 55%
2034 – 2039	30.1	42.9	37.2	40.1	22 - 45%
2039 – 2043	28.4	42.9	37.7	43.2	0 - 36%

3.4.11 The ExA referenced that the 2016 actuals baseline is unaffected by recorded breaches of noise and sought views on using this as the baseline year across all data.

3.4.12 The Applicant confirmed that, as can be seen in the response to WQ NO.1.9 **[REP4-060]**, the use of the 2016 actuals baseline results in the overall same conclusion as when using the 2019 Consented baseline, so there would be no benefit in repeating the entire assessment with this additional baseline.

3.4.13 The Applicant noted that there is sufficient information across the various written submissions to cover the various baselines and their implications:

q. 2019 Actuals and 2019 Baseline is used in **Chapter 16** of the **ES [REP1-003];**

r. 2013 and 2016 Actuals baseline is addressed in response to WQ NO.1.8 and NO.1.9 **[REP4-060]**; and

3.4.14 The P19 consented baseline is addressed in **Implications of the P19 Approval for the DCO [REP4-093]**, ISH8 and this post hearing submission.

3.4.15 The Applicant stated that it was important to understand that the baseline adopted does not influence the do something/do minimum scenarios, a point acknowledged by the consultant for the Combined Authorities.

3.4.16 The ExA expressed concern that the consented baseline over inflates the number of aircraft which could influence secondary metrics such as overflights and N-above contours and asked if the shape of the contour would be different with consented fleet rather than the actual fleet.

3.4.17 The Applicant stated that whilst the size of the contour is different, its shape is not expected to be different as it is only the proportion of fleet that is altered, not the number of movements, or the direction in which they fly, or the proportion of arrivals vs departures, or the relative proportion of movements on each departure route.

3.4.18 The Applicant confirmed that guidance from the Civil Aviation Authority[34] and Government[5] is clear that metrics such as overflights and N-above contours are secondary metrics and should not be used for the identification of significant effects on health and quality of life.

3.4.19 The ExA recognised this would not be applicable to health but queried the impact on outdoor enjoyment. For example, could it affect the Chilterns AONB? The Applicant confirmed it has not downgraded number of movements in the 2019 Consented baseline but changed the fleet mix, so it has not affected the overflight baseline.

3.4.20 Furthermore, if a different approach was taken such as a 2016 actuals baseline based on the lower number of aircraft movements that operated that year, this would result in a lower passenger number of approximately 16 mppa, meaning that the assessment of benefits and other environmental impacts from the Proposed Development would be inconsistent with noise.

3.4.21 The Applicant confirmed that it had been in discussion with the CAA on various points and has addressed the historic concerns on noise modelling raised by the CAA and this is recorded in the SoCG to be submitted at deadline 6 **[TR020001/APP/8.10]**.

3.5 Aircraft modelling assumptions and validation including assumptions relating to load factors, runway operation, the A321Neo and implications of the 19 mppa consented fleet forecasts (e.g. Appendix 8B of CD1.10 Volume 3 Environmental Statement - Figures And Appendices (January 2021) (ESA2))

3.5.1 The ExA noted that in **[REP4-072]** the Applicant referenced a load factor of 91.5% and queried how this would affect the noise model.

3.5.2 The Applicant confirmed that whilst the AEDT default load factor is 65%, the modelling does not use the default and the effect of load factor is considered in the model validation process through the adjustment of departure profiles (altitude and ground speed) and aircraft noise emissions to match what is actually flown.

3.5.3 The Applicant noted that load factors are not forecast to materially increase with expansion (see paragraphs 6.6.15 and 6.6.16 of the **Need Case [AS-125]**). Any future load factor changes will be accounted for in the ongoing annual noise model validation.

3.5.4 It was confirmed that a load factor of 91.5% is a precautionary number used for terminal capacity planning which differs from the 87% figure referenced in paragraph 6.6.14 of the **Need Case [AS-125]**.

3.5.5 The ExA asked if larger planes would change the operational procedures followed at the airport and whether this had been considered in modelling work.

3.5.6 The Applicant confirmed that the validation process accounts for majority of aircraft currently flying, including larger aircraft that are in the future forecast. The Applicant is therefore confident that the modelling accounts for larger aircraft. The Applicant also confirmed that there is no need to adjust the inset thresholds to account for the larger aircraft.

3.5.7 The ExA referenced the airport operator's draft 2024-2029 Noise Action Plan submitted in response to WQ GCG.1.6 **[REP5-090]** which notes that a full runway length trial demonstrated a small reduction in noise close to the airport and queried whether that had been taken into account in the noise modelling.

3.5.8 The Applicant confirmed that this small noise benefit has not been taken into account, and this remains as a potential mitigation measured that could be employed by the airport operator to minimise noise and stay within the noise contour area limits in the **Green Controlled Growth Framework [REP5-022]**

3.5.9 **Action point 5: Discuss with operator the geographic extent of the reduction in noise from the use of the full runway length and provide a map showing where this noise reduction could apply.**

3.5.10 The ExA referred to: **REP5-072** and quarterly monitoring report benefit from some A321neo aircraft. The Applicant confirmed it is aware of the engine variant issue and noted that the position on the A321neo and how it has been modelled is set out in **Chapter 16** of the **ES [REP1-003]**. The Applicant reiterated that the performance of the A321neo is based on actual noise measurements in assessment Phase 1. In assessment Phases 2a/2b it is assumed that the issues with the A321neo will have been resolved, or that these aircraft would be replaced with alternative quieter aircraft in line with standard aircraft lifecycles of 10-15 years. This assumption is then secured by the Noise Envelope contour area limits which are based on the assumption that the A321neo noise issue would be resolved.

3.5.11 The Applicant has only applied actual measurements in this context rather than projections until 2039, with projections assuming the engine variant issue is rectified then applied after 2039 including the fleet replacement.

3.5.12 The ExA noted, from the P19 application Table 8B.1 of the ES addendum 4, Appendix B, a large difference in future fleet mix scenarios for 2028 which appears to be inconsistent with what was included in this application. Given the figures refer to the same airport should the numbers be more consistent?

3.5.13 The Applicant confirmed it had accounted for the fleet mix proposed. The P19 application recorded 50-53% transition of commercial passenger aircraft in in 2025, and 88% in 2028. The figures for the application for development consent is 69% in 2027 for the Core Planning Case which is robust against the P19 trendline.

3.5.14 **Action point 8: Submit more detailed comparison table regarding fleetmix (19 MPPA permission vs Application)**

3.5.15 **Post hearing submission:** the requested comparison table is provided in **Appendix A** to this document.

3.5.16 LADACAN queried the 38.9% modernised aircraft today stating it did not believe it was correct (the figure was closer to 30%). The Applicant confirmed that the figure had been obtained from the airport operator but, as the figures are rolling totals, there will be differences from year-to-date figures as the pace of refleeting has increased over the summer and into the autumn.

3.5.17 **Post hearing submission**: The Applicant has discussed this discrepancy with LADACAN and has confirmed that the 30% figure for Q3 2023 referred to the proportion of all aircraft movements, including business aviation and cargo flights, whereas the figure of 38.9% referred to is the proportion of commercial passenger aircraft. These figures are consistent and the matter has been agreed in discussions with LADACAN.

3.5.18 The local authorities confirmed that they had no issues to raise with regards to fleet mix.

3.6 The balance of growth vs future noise reduction

3.6.1 The ExA confirmed that this item would be considered at ISH9 on Green Controlled Growth.

3.7 Operational noise mitigation measures including for Park Homes

3.7.1 The ExA queried whether an air traffic movement cap would be appropriate for Luton.

3.7.2 The Applicant noted that movement limits are poorly correlated with noise impact metrics (as demonstrated in **Noise Envelope - Improvements and worked example [REP2-032]**) and provide no incentive for the adoption of quieter aircraft and therefore no further movement limits are proposed (over and above the movement limit in the night quota period), though annual movements will be reported as set out in the **Aircraft Noise Monitoring Plan [REP5-028]**, secured by a DCO Requirement.

3.7.3 This is in line with CAA's CAP1731 document[6], which includes a review of suitable noise metrics for limiting and controlling noise, and which notes on page 58 that the number of movements: *"has good correlation with day noise* *quota count and night noise quota count, when broken down into the number of movements per day and night respectively. It shows reasonable correlation with day noise contour area, but it gives no mechanism to limit impact within a given area. It also does not have any correlation with people exposed, so it would not be effective in controlling population noise exposure or in driving noise reduction. Overall, the number of movements is a metric that should be monitored to understand the growth of the aviation market, but it does not provide effective controls to limit noise generation, noise exposure nor noise impacts."*

3.7.4 The Applicant reiterated that the best correlated metric with daytime and night-time noise effects is the L_{Aeq} metric, as demonstrated in research by the CAA which has been reanalysed and reconfirmed as recently as 2021 and 2022 fsh[7] (Ref 4, Ref 5).

3.7.5 **Post hearing submission:** the use of the L_{Aeq} metric and the concept of the LOAEL is also applicable to the experience in outdoor amenity spaces such as the Chilterns AONB. Planning Practice Guidance – Noise[8] notes that below the LOAEL *"Noise can be heard, but does not cause any change in behaviour, attitude or other physiological response. Can slightly affect the acoustic character of the area but not such that there is a change in the quality of life."*

3.7.6 Operational noise mitigation measures are summarised in Section 16.8 and 16.10 of **Chapter 16** of the **ES** [**REP1-003**] and Comparison of Consented and Proposed Operational Noise Controls [**REP5-014**] and include:

a. the 'Noise Envelope' which is secured through the **Green Controlled Growth Framework [REP5-022]**, is a legally binding framework of enforceable limits and controls to manage air noise and other environmental topics;

b. a substantially improved noise insulation scheme (Draft Compensation Policies Measures and Community First [REP4-042]);

c. New noise controls were committed to at deadline 5 and a new **Air Noise Management Plan (ANMP)**, submitted at Deadline 6 **[TR020001/APP/8.125],** to be secured by a DCO Requirement.

d. This **ANMP** includes a limit of 9,650 aircraft movements (previously a standalone Draft DCO Requirement but now part of ANMP), 3,500 total QC annually during the night quota period (from 23:30 and 06:00) to limit night-time aircraft noise levels, a ban on QC2 and above aircraft during the full night-period (23:00 – 07:00) and track violation penalties plus departure noise violation limits.

3.7.7 The Combined Authorities stated that the imposition of an air traffic movement cap is not a stand-alone measure and needs to be considered with other controls as mentioned by the Applicant. Air traffic movements do, however, provide a degree of certainty to the local population.

3.7.8 The Applicant confirmed it is not setting aside traffic movement caps, there are movement limits, as mentioned above, but supported by the numerous control measures highlighted earlier. The Applicant's view is that nothing further is required to provide a robust combination of noise controls.

3.7.9 The ExA asked whether noise from the 24-hour car park (such as idling engine noise, car doors slamming) has been assessed.

3.7.10 The Applicant confirmed that this was not a noise source that was scoped in to the assessment as it is not likely that any adverse likely significant effects would occur from these noise sources. However, road traffic accessing the airport and car parks has been assessed. The local authorities stated that noise from car parks is not typically scoped into noise assessments and the local authorities are not aware of this ever having been done before for airports.

3.7.11 The ExA raised the issue of suitable insulation for Park Homes and asked whether this has been assessed?

3.7.12 The Applicant confirmed that there is consideration within the noise insulation policy as to what needs to be provided at the various insulation scheme thresholds above and below the SOAEL. The Applicant confirmed that there are no park homes within SOAEL, as confirmed in its response to Written Question NO.1.29 **[REP4-060]**. There are some between LOAEL and SOAEL – and so there is a requirement to mitigate and minimise noise as far as reasonably practicable. The compensation policy requires surveys to be undertaken to determine what is practicable and possible at these homes. The majority of the park homes are understood to be substantial and capable of being insulated. If the surveys determine that it is not possible to provide further noise insulation due to their construction - then that still complies with the policy requirement to mitigate and minimise within the context of sustainable development (i.e. as far as reasonably practicable).

3.8 The robustness of the non-residential receptor screening process (with specific reference to the Sue Ryder Neurological Care Centre at Stagenhoe, Woodside Nursing and Residential Home in Slip End)

3.8.1 The ExA stated that the list of non-receptors appears to exclude certain care and nursing homes such as the Sue Ryder Neurological Care Centre, and the Woodside Nursing Home.

3.8.2 The Applicant explained that Table 16.7 of **Chapter 16** of the **ES [REP1-003]** clarifies that for the purpose of the noise assessment, nursing homes and care homes are treated as residential receptors (this includes the two referenced properties).

3.8.3 This is on the assumption that people will be living and sleeping in these spaces on a medium to long-term basis and hence residential assessment criteria is appropriate and standard practice.

3.8.4 For this reason, there is no non-residential screening criteria for nursing homes and care homes as they are covered in the residential assessment.

3.8.5 In response to a query on whether the assessment for aircraft noise can apply to outdoor amenity spaces such as woodlands, the Applicant noted that the thresholds for the noise assessment are derived from CAA research (Ref 2) which takes into account community response and does not just apply to people in their homes, it takes into account people's experience indoors and outdoors and enjoying outdoor space. There are no other thresholds or methodologies in aircraft noise policy or guidance that suggests a separate approach should be taken for woodland receptors, for example. Finally, the noise controls in the Noise Envelope and the **ANMP** submitted at Deadline 6 **[TR020001/APP/8.125]** would benefit both indoor and outdoor space. The Applicant also signposted to the consideration of tranquillity in paragraph 16.5.70 onwards of **Chapter 16** of the **ES [REP1-003].**

4 Agenda Item 3: HEALTH AND COMMUNITY

4.1 Introduction

4.1.1 Before starting on the agenda item, the ExA identified some significant health and community effects - Section 13.9 and 13.11 still incorrectly reported. The Applicant confirmed that these would be amended for Deadline 7.

4.1.2 **Action point 10: Revise ES Chapter 13 to remove references to a significant perception effect during operation, consistent with the errata document. In addition, update the document to include the updated future baseline information submitted to the Examination at D4 [REP4-068]. Update of ES to also include any adjustments that would result from Action Points 14 or 15.**

4.1.3 The ExA then moved on commence discussions on the first agenda item.

4.2 Whether local datasets and health strategies should be used to inform the health and community assessment

4.2.1 The Applicant confirmed that various meetings took place with the LPAs to explain data sets used in study areas. The Applicant believes the data sets are consistent with Joint Strategic Needs Assessment (JSNA) data. The LPAs asked for additional data which the Applicant has provided and will be reflected in SoCGs at deadline 6.

4.2.2 Local study area is local to the Proposed Development and is where health effects on known receptors are likely to occur, so uses detailed data to assess receptor sensitivity. If the Applicant had identified effects outside of that study area, it would have sought more detailed data for relevant receptor locations within the wider study area. This was not required because none were identified outside the local study area.

4.2.3 The Applicant confirmed that the wider study area included Luton, Central Bedfordshire, Hertfordshire and Buckinghamshire. The wider study area was too large to obtain and consider detailed ward data and it would not have informed the assessment further. Cannot be specific as to where effects, for example from employment benefits, will specifically take place. JSNA data was not used as the Applicant considered national source data to provide consistency across the local authorities. The position was explained and agreed with the LPAs.

4.2.4 The ExA asked the various LPAs to confirm their position, LBC confirmed it was satisfied and position is recorded in SoCG. The Combined Authorities confirmed position was proportionate and agreed. Central Bedfordshire Council (CBC) confirmed it will provide feedback on data received. Buckinghamshire Council (BC) had no comment.

4.2.5 The ExA asked if the health Chapter of the ES contained any specific mitigation proposals. The Applicant confirmed that **Chapter 13 [AS-078]** largely refers to other chapters for proposed mitigation especially noise to avoid unnecessary duplication. There is a specific community engagement mitigation set out in **CoCP [REP4-011]**. Details will be defined at later stage by the Applicant for construction and operational phases of the Proposed Development.

4.2.6 The Applicant confirmed that the **Mitigation Route Map [AS-047]** identifies specified mitigation for health effects (pages 44 to 48).

4.3 The mapped extent of N-above 80dB LASmax contour linked to awakenings

4.3.1 The ExA queried whether the reported awakenings relate to the N-above 80dB LASmax contour.

4.3.2 The Applicant confirmed that awakenings are calculated using a methodology by Basner and McGuire, published by the World Health Organization (WHO) in 2018[9], which is supplied in **Appendix B** to this document. The equation used to predict awakenings is equation 2 on page 13 of the research paper. The methodology is more robust than the N-above contours, which only take into account noise levels above a certain L_{Amax} threshold. The Basner methodology takes into account every aircraft movement regardless of its maximum noise level.

4.3.3 **Action point 16: Submit Basner reference that sets out how awakenings have been assessed, or relevant extracts if restricted due to copyright.**

4.3.4 **Post hearing submission:** the research paper is provided in **Appendix B** to this document.

4.4 Measures to mitigate impacts on the health and wellbeing of the local communities surrounding the airport

4.4.1 The health assessment **[AS-078]** does not identify any significant residual adverse health effects during operation. The Applicant considers, therefore, that no additional measures are required to mitigate operational health effects.

4.4.2 The Applicant is aware that various operational issues/concerns have been raised by the LPAs. The Applicant's position is set out in its Deadline 5 response - Comments on ExA Questions [**REP5-052**] (ExAQ HAC 1.15).

4.4.3 Discussions are ongoing with the LPAs and UKHSA.

4.5 The potential need for future health effects monitoring as suggested by the UK Health Security Agency and any triggers for remedial action [REP4-219].

4.5.1 The Applicant's position is set out in its Deadline 4 and 5 responses regarding ExA Written Question **HAC 1.14** [**REP4-219**], [**REP5-052**].

4.5.2 In response to various points raised by third parties, the Applicant pointed out that Reg 21 (3)(c) of the Infrastructure Planning (EIA) Regulations 2017 provides monitoring arrangements that are carried out under obligation under UK law. The Applicant is not aware of any other UK studies that require this.

4.5.3 **Action point 19: Confirm whether Regulation 21(c) of the Infrastructure Planning (EIA) Regulations 2017 would be engaged by the request from UKHSA for monitoring.**

4.5.4 The Applicant explained it is important to distinguish between engagement and monitoring, since both have been raised in this discussion. The Applicant recognises the need for engagement as a way to mitigate adverse effects on mental wellbeing.-The existing airport operator is delivering London Luton Airport Consultative Committee, Noise and Track Sub-Committee and Community Noise Surgeries in person.

4.5.5 With monitoring there is an issue of proportionality in the EIA, and a complexity associated with monitoring health outcomes and attributing to a cause. One can monitor a determinant e.g. noise, but to attribute causation to the Proposed Development is more complex.

4.5.6 Monitoring that provides robust evidence of causality is also very resource intensive, requiring a complex study design and a need to eliminate things like bias and confounding. The airport operator is supporting existing studies e.g. DfT aviation night noise study, and other national studies.

4.5.7 The Applicant considers that this is best done at national level considering reliability of results, a larger study population and so forth. Airport specific study may also not provide general information that would inform national policy and guidance. The end goal is to act on the results.

4.5.8 Potentially there is a risk that handing out surveys to residents may duplicate results/ conflict and undermine results of existing national studies that include the population around Luton. The Applicant does not yet have results from other studies, e.g. Heathrow, so cannot comment at this time on how to apply this information.

4.5.9 **Action point 20: Applicant and UKHSA/ Office of Health and Improvement and Disparities (OHID) to meet to discuss possible health monitoring and an agreed position statement/ way forward**

5 AGENDA ITEM 4: AIR QUALITY

5.1 Whether significant effects are likely due to 24 hour working using static conveyor(s) for non-contaminated material

5.1.1 The Applicant confirmed that significant effects are highly unlikely with reasonable worst case assumptions in the Non-Road Mobile Machinery modelling. Any use of conveyors is likely to be electric and hence have no local emissions. The modelling assumed the use of dump trucks (referred to as dumpers) which represent more emissions than would come from the use of a conveyor, as detailed in Table 3.24 of **Appendix 7.1** of the **ES [AS-028**].

5.1.2 LBC confirmed that it agreed with Applicant and that best practice guidance had been followed. There were no comments from any of the other LPAs.

5.2 The extent to which freight consolidation would be used to reduce construction traffic and traffic related emissions;

5.2.1 The Applicant confirmed that the air quality assessment has not assumed any freight consolidation. It has concluded no significant effects (see **Chapter 7** of the **ES [AS-076]**).

5.3 An update on any air quality assessments relating to offsite highway works

5.3.1 The Applicant confirmed that a note summarising the effects on the Hitchin Air Quality Management Area (AQMA) was provided to Host Authorities on 29 November 2023. The note sets out in detail the receptors modelled in Hitchin AQMA. No predicted significant effects were identified as a result of the Proposed Development. It is understood that North Hertfordshire Council is considering whether to revoke the AQMA through the Defra process as it is well below threshold levels for annual mean NO_2 and concentrations have remained below for over three years.

5.3.2 **Action point 21: Submit a copy of the note prepared by the Applicant on the Hitchin Air Quality Management Area (AQMA). Joint Host Authorities to provide their response to the note.**

5.4 An update from the Applicant regarding the potential for odour and flies from the proposed water treatment plant

5.4.1 The Applicant confirmed that the preferred option within the current drainage proposal (refer to the **Drainage Design Statement [REP5-096]**) requires foul water to go to Thames Water (TW) treatment plant which would negate need for treatment. It noted that a reserve option remains as treatment with discharge of water to ground.

5.4.2 The Applicant confirmed that permit discussions with the Environment Agency have not started but will be picked up in future regular meetings.

5.4.3 **Action point 23: Response/ update on the implications of the change request for odour and flies and any discussions with the Environment Agency regarding potential odour controls.**

5.4.4 The Applicant confirmed that detailed design of any wastewater plant will be subject to the approval of the LPA through Requirement 5 of the draft Development Consent Order.

5.5 Whether there would be an ongoing need to investigate, report and mitigate kerosene odour

5.5.1 **Post hearing Submission**: Actions 22 and 25 cover the same issue so are considered together in this section of the note.

5.5.2 The Applicant confirmed that complaints are handled, at present by the airport operator through its noise complaint procedure, which is available online. It was noted there were no significant effects predicted as a result of the Proposed Development.

5.5.3 The Applicant confirmed that an update to the odour management procedure as requested by LBC is to be provided at Deadline 6.

5.5.4 **Action point 22: Submit a copy of the Applicant's proposed outline fuel odour control procedure, LBC to provide a response. Discuss a mechanism for LBC to engage with the procedure and explain how the procedure would integrate with any airport environmental management system.**

5.5.5 The ExA asked if there is a mechanism to engage the local authority in the odour complaint process. The Applicant confirmed that there is no process currently, but the Applicant will discuss this through the ongoing SoCG process.

5.5.6 LBC confirmed they have very few odour complaints and requested that the operator review any complaints in the first instance and also provide a reference for how to contact the council to ensure their statutory duty was complied with.

5.5.7 The ExA asked what actions would be taken if complaints were received. The Applicant noted that it would be dependent on identifying the cause in the first instance and putting in place suitable remedial action where required, as under normal conditions, best practices are followed, and no significant effects are predicted.

5.5.8 The Applicant has consulted the CAA for an update of any kerosene dumps by airlines and is yet to receive a response. The Applicant will continue pursuing this matter with the CAA.

5.5.9 **Action point 25: Update regarding how potential complaints in relation to odour could be made and managed, and how this would be secured.**

6 AGENDA ITEM 5: BIODIVERSITY

6.1 Review how the effect of emissions from an 'increase in traffic' on woodlands is incorporated in the assessment in respect of car parks

6.1.1 The Applicant confirmed that emissions from car parks are much less than for on the road as cars are typically stationary. Car parks were included in the modelling, detailed in **Appendix 7.1 [AS-028]** of **Chapter 7** of the **ES [AS-076]**. A conservative approach has been adopted or long-term car parks, with turnover rate of 1.15 spaces a day assumed (which is based on the rate of a short term car park).

6.1.2 The ExA asked about Winch Hill Wood adjacent to Car Park 10 and asked the Applicant to confirm the distance between the two.

6.1.3 **Action point 26: Confirm proximity of Winch Hill Wood to the nearest proposed car park and explain the implications for the assessment of effects if it is closer than the 64m advised at D5.**

6.1.4 The ExA expressed concern with hydrology and the apparent 'cliff edge' next to Winch Hill Wood [**REP4-070**]. The ExA cannot tell if the change in topography affects the wood.

6.1.5 **Action point 27: Confirm the extent of likely topographical changes in proximity to Winch Hill Wood, Provide and more detailed assessment of the effects of this on the hydrology beneath the Woodland and the potential effects of this, or explain why this is not required.**

6.1.6 **Action point 28: Review whether any other sensitive sites should also be considered in terms of the potential impacts of significant topographical changes on hydrology.**

6.2 Timescale of updates to guidance on buffer zones for woodlands referred to by the Forestry Commission [REP4-169].

6.2.1 The Applicant confirmed that it has tried to find out from the Forestry Commission an update on when the guidance will be updated. There is no information in the public domain that the Applicant is aware of.

6.2.2 The ExA commented that the Forestry Commission and the Woodland Trust argue that the proposed 15m buffer is not sufficient, but the ExA has not received enough information to conclude if such a buffer is sufficient.

6.2.3 The ExA is concerned with all woodlands and trees that need protecting. The Applicant confirmed that it is not predicting any significant air quality effect from the car parks. Root damage area is considered and embedded in **Design Principles [REP5-034]. Action point 30: It has been confirmed that all protect woodland and trees have a buffer zone of at least 15m. However, Natural England guidance and IP representations recommend that this is a minimum and may need to be extended depending on the**

circumstances. Provide further justification regarding the extent of buffer zones around woodland and protect trees.

6.2.4 In response to **REP4-070** the ExA also enquired the possible translocation and final destination of Tree 343.

6.2.5 **Action point 31: Confirm whether a location for the relocation of tree T343 has been identified and, if not, whether this is something that could be secured in the draft DCO.**

7 AGENDA ITEM 6: WATER

7.1 Update on discussions with Thames Water regarding disposal of liquid discharges

7.1.1 The ExA asked for an update on disposal of foul water and contaminated surface water to the TW network. What is likely to go into the network, how much can be stored and what is the discharging rate.

7.1.2 The Applicant confirmed that load from passenger demand in assessment Phase 1 would only exceed the foul discharge rate for a 1hr period at peak time, therefore storage capacity has been included so that this foul is stored for discharge during an off-peak period. As such, the Applicant considered that no capacity increase at East Hyde is needed in assessment Phase 1.

7.1.3 For assessment Phase 2a, there are two Asset Management Plan (AMP) cycles (AMP 2025-2030 and AMP 2030-2035) which present two opportunities to identify and secure improvements to TW systems needed ahead of assessment Phase 2a commencement in 2035 and delivery before this phase comes online. Modelling of the network capacity has identified some drainage areas requiring upgrades, but these could be undertaken within TW Permitted Development rights. The Applicant confirmed that this will be captured in the TW SoCG submitted at Deadline 6 **[TR020001/APP/8.06]**.

7.1.4 The Applicant confirmed that flows and loads have been provided to TW for modelling constraints at East Hyde. An option is to have a water treatment works onsite to provide pre-treatment of the contaminated surface water (to reduce contaminant load) before discharging to the TW network.

7.2 Update on any discussions with the Environment Agency (EA), including regarding discharge of treated surface water runoff and foul effluent to the ground

7.2.1 The Applicant confirmed it is engaging with the EA regularly (at least fortnightly) and moving towards agreement on many outstanding SoCG items. Progress will be captured in the SoCG submitted at D6 **[TR020001/APP/8.07]**.

7.2.2 It was confirmed that the EA has a strong preference for the Deadline 4 **Drainage Design Statement [REP5-096**] preferred discharge option, where foul water and contaminated surface water is discharged to the TW foul network. If the reserve option (where foul and contaminated surface water are treated and discharged to ground) were utilised, it is agreed that further information (such as baseline monitoring etc) would be needed at detailed design (secured by the **Design Principles [REP5-034]**).

7.2.3 The EA is currently reviewing the **Drainage Design Statement [REP5-096**], **Hydrogeological Risk Assessment – Drainage** [**REP4-035**] and drainage related **Design Principles** [**REP5-034**] submitted at D4 and D5, with an aim between parties to agree that there is a pathway for consenting for both discharge options (to be captured in SoCG by Deadline 9. Further design refinement would be required at detailed design stage, in accordance with the **Design Principles [REP5-034]**.

7.3 Management of the risk to water quality from works in and around landfill materials

7.3.1 The ExA asked for an update on the documents being produced associated with proposed works within the historical landfill, including piling, the waste recovery plan and hydrogeological risk assessment and ongoing discussions with the EA.

7.3.2 The Applicant confirmed it is producing a waste recovery plan which is in the final stages of review, and the Applicant intends to submit it to the EA shortly.

7.3.3 The Applicant noted that the EA has provided further advice on guidance they have developed internally about piling through landfill (not publicly available) and is currently considering how this is implemented.

7.3.4 The Applicant is aware it may need a groundwater authorisation for the proposed works; this would require measures to protect and limit risks to groundwater.

7.4 The pattern of discharge from the infiltration tanks and groundwater mounding;

7.4.1 The ExA commented that, with regards to the underground storage tanks in the landfill, the EA's preference is for placement not within the landfill.

7.4.2 The Applicant noted it had reviewed the Environment Agency's response to the ExA's Written Questions **[REP4-166]** and referred to the Applicant's written response to the ExA Written Question on the matter [**REP4-066]. **The Applicant has included a number of drainage related **Design Principles [REP5-034]** to manage risks to the landfill from the proposed tank such as flexible joints and lining.

7.4.3 The EA is currently reviewing the **Design Principles [REP5-034]**, and there are options for further measures include monitoring and proactive maintenance.

7.4.4 The ExA asked about groundwater mounding, whether changes to topography had been taken into account and queried the potential implications on the water table and flooding.

7.4.5 **Action point 33: Review the proposed changes to the landform upgradient of the infiltration tanks and describe how this might affect**

groundwater levels, including whether there would be any implications for the risk of flooding.

7.4.6 The ExA asked what was meant by the infiltration tanks remaining mostly dry in all but the most severe storms.

7.4.7 The Applicant noted that there is rainwater harvesting and surface water reuse planned to limit potable water requirements from the Affinity Water network. Refinement of design will consider different options for water reuse. Only after the harvesting system is full would excess runoff discharge to ground. The size of the infiltration tank means that shortly after most rainfall events the infiltration tank would be empty. The saturated zone could fill in 2-3 hours but would not be discharged.

7.5 Progress on assessing opportunities for improvements to the surface water drainage system to avoid diversion of 9 hectares of the River Lea catchment to the River Mimram

7.5.1 Following on from the Written Question WE 1.9 regarding alteration of surface water catchments, which the Applicant responded to at Deadline 4 [**REP 4-066]** noting that the airport operator was currently looking at drainage upgrades as part of Project Curium.

7.5.2 The Applicant understands that the airport operator has engaged designers for the western drainage works which are planned to be constructed in 2024/2025. This will avoid diversion of the 9 hectares from the River Lea catchment.

7.6 Updates to the Water Framework Directive compliance assessment to incorporate the 2022 interim classifications and the latest River Basin Management Plan

7.6.1 The Applicant confirmed that the **Water Framework Directive (WFD) Compliance Assessment [REP4-027]** updated at Deadline 4 did not incorporate the most recent 2022 interim classifications and updated River Basin Management Plans. The Applicant undertook a comparison which was disseminated to the EA and concluded there was no material change to the assessment when compared to the 2019 baseline utilised in the EIA. This is captured in the SoCG with the EA, which the Applicant confirmed would be submitted at Deadline 6 **[TR020001/APP/8.07]**.

7.7 Responses from Interested Parties (IPs), including the local authorities, the Environment Agency and Affinity Water to the updated ‘Design Principles’ [REP5-035] in relation to drainage works.

7.7.1 Not discussed.

8 AGENDA ITEM 7: LAND-USE

8.1 Update on discussions with Natural England regarding best, most versatile (BMV) land and alternatives to use of this

8.1.1 The ExA read out a statement from Natural England (NE) in lieu of its attendance at the hearing which confirmed that the NE soils specialist is now satisfied with soil balance breakdown and happy that detail can be submitted post consent.

8.1.2 The Applicant confirmed it is updating the **Outline Soil Management Plan [APP-060]**, which is referred to by Requirement 7 of the **Draft DCO [REP5-003].**

8.1.3 The ExA noted that Deadline 4 Action 17 [**REP4-070]** stated BMV land was not considered in option appraisal. Retaining Wigmore Valley Park would affect agricultural land. Environmental preference for loss of BMV and carbon balance. How balanced are these aspects?

8.1.4 **Action point 34: Clarify whether Best and Most Versatile (BMV) land was a factor when optioneering the land requirements. If not, confirm whether it should have been and if this would have resulted in a different outcome.**

8.1.5 **Action point 35: Explain how retention of Wigmore Valley Park would have resulted in a greater loss of BMV land**.

8.1.6 **Action point 36: [REP4-070] advises that the area set aside for replacement park in the Green Horizons Park permission was required for excavation of material to construct the aviation platform. This was considered environmentally preferable to importing material. However, the overall environmental impact is also a function of the effects on BMV land. Please confirm if this factor was considered as part of the balance in this case.**

8.2 Consideration of whether the proposal would be inappropriate development in the Green Belt and, if it is, whether the case for very special circumstances exists, with particular reference to the consideration of alternatives

8.2.1 The ExA had a single question in relation to the Above Ground Installation (AGI) and whether it would be inappropriate development in the Green Belt.

8.2.2 The Applicant acknowledged that the AGI is inappropriate development. It is required to facilitate connection into the existing fuel pipeline which runs north to south through the Green Belt. Therefore, there are no alternatives outside the Green Belt.

8.2.3 The AGI location was selected for a number of reasons including proximity to the airport; avoiding the airport public safety zone; avoiding intersecting the runway centre line and the presence of strong screening from woodland blocks.

8.2.4 The Applicant considers that the Green Belt harm is “limited” and is clearly and demonstrably outweighed by benefits associated with significantly reducing fuel tanker movements on the highway network (estimated to be 134 fuel tanker movements per day).

8.2.5 The Applicant explained that the AGI is required for the point where the new fuel pipeline spur will join the existing aviation fuel pipeline at its closest point to the airport. The Applicant explained that the existing aviation fuel pipeline runs for at least 3km to the north and 3km to the south of the Green Belt. As such, for the connecting fuel pipeline to join with the existing aviation fuel pipeline in land outside the Green Belt would require a connection more than 3km in length with the myriad of associated environmental impacts that would arise from the construction of such a long extension.

9 AGENDA ITEM 8: CLIMATE CHANGE AND GREENHOUSE GAS EMISSIONS

9.1 Sensitivity of the assessment to future operational requirements and pace of technological improvements

9.1.1 The Applicant explained that the recent decisions re Bristol Airport and P19 had endorsed the proposed approach for the assessment of aviation emissions. Both the UK Emissions Trading Scheme (UK ETS) and Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) are recognised and separate control regimes. The Government has made this clear in Making Best Use (MBU)[10] (paragraph 120) and the Bristol Decision[11] (paragraph 98). Key to this is that emissions from aviation are to be manged at a national level not at an individual application level, as made clear in MBU at paragraph 1.11.

9.1.2 It is important to understand from the Jet Zero Strategy[12] how allowances under UK ETS will align. As described in paragraph 188 of NPPF[13] where regimes that provide pollution or emissions control are in place, it should be assumed that these regimes would operate effectively.

9.1.3 Carbon is capped by UK ETS. If technical improvements do not come along in line with the government assumptions that could lead to higher carbon pricing. The Applicant’s response in **[REP4-078]** to points raised to action point 15 explain this further. The Applicant stressed that it is important to have regard to the fact that the carbon values used for the purpose of forecasting future demand are not simply the current UK ETS traded prices but trend to the BEIS target carbon values for appraisal purposes that reflect the costs necessary to achieve abatement sufficient to achieve the Government’s carbon reduction targets. The Applicant has tested various sensitivities (Monte Carlo tests) and if carbon prices are higher then this will mean that the planned growth will not be achieved. **REP4-104** describes this slower growth due to higher prices. The costs of carbon and/or its abatements are fully internalised within the demand forecasts

9.1.4 The Applicant explained that in Department for Transport’s Jet Zero - One Year On Report (appended to this document), it was made clear that CORSIA was seen as an interim step that may be replaced by something more like UK ETS.

9.1.5 **Action point 37: Provide a copy of the Government's update 'Jet Zero Strategy: one year on' (July 2023) with signposting to the sections referred to by the Applicant regarding likely future evolution of policy.**

9.1.6 **Post hearing Submission**: It is clear from the Department for Transport's Jet Zero – One Year On[14] report of July 2023 that the intention is to continue to tighten up controls on flights not currently covered by the UK ETS, including the CORSIA scheme. This is set out on page 29 of Jet Zero – One Year On.

9.1.7 The Applicant responded to comments about what would happen if higher prices occurred, or technology did not develop as quickly as expected. The **Applicant's response to Deadline 3 Submissions - Appendix I Buckinghamshire Council [REP4-104]** responded to these points so, for example, if technological changes do not come forward as quickly as expected then this is reflected in Slower Growth Case. The Applicant has assessed many scenarios, higher prices, delayed technology and if cost of buying permits increases. The Applicant has not assessed if none of them come forward, however that scenario would not be a testable one.

9.2 Use of offsetting for Scope 3 emissions

9.2.1 This item was not discussed.

9.3 Likelihood of the 2040 net zero target for ground operations being achieved

9.3.1 The ExA referred to modelling of GHG emissions showing residual emissions for ground operations in 2040 and asked for clarity on how possible or likely it was that the Applicant can meet such targets?

9.3.2 The Applicant stated that the Government is still evolving strategy for how the 2040 zero emissions target will be met for airport operations. In the Jet Zero[15] strategy the Government stated, *"to aid this we will be publishing a Call for Evidence on the best approach to implementing the target in Autumn 2022."*(page 65). Part of the Call for Evidence is consulting on a definition of Airport Operations to understand what will be included in scope. The consultation ran until May 2023.

9.3.3 In Jet Zero One Year On[16], government stated they would *"analyse responses to the Call for Evidence on the zero-emissions operation target, publish a consultation early next year, setting out proposals for implementing the target."*

9.3.4 This is now expected, possibly before the end of this year.

9.3.5 The Applicant acknowledged that there will be some residual emissions in 2040. This is presented in **Chapter 12** of the **ES**, Table 12.19 [**REP3-007**] with emissions from airport operations reducing from 17,149 in 2019, to 2,978 in 2040. The majority of residual emissions arise from the generation of grid electricity supplied to the airport. Other sources included emissions from firefighting foams and de-icer. Offline renewables is one option, that may come forward to reduce these emissions. However, until the Government confirms exactly what will be included within the scope of zero emissions Airports it is not possible to say with certainty what mitigation will be put in place. It is possible that such emissions may be excluded from the target across all airports. The **GCG Framework [REP5-022]** also includes controls and commitments are in place to review government changes in line with Jet Zero.

9.3.6 The ExA stated that there is nothing to prevent expansion if the Applicant does not meet that target by 2040.

9.3.7 **Post hearing submission:** The majority of residual emissions from airport operations in 2040 result from the consumption of grid electricity, with other emissions resulting from the use of de-icer, fire training, aircraft engine tests and fugitive emissions of refrigerants.

9.3.8 GCG places a requirement on the airport operator to undertake and submit to the Environmental Scrutiny Group a review of both the definition of ‘Airport Operations’ and the associated limit from 2040 onwards within three months of the government publishing updated policy or guidance that clarifies the scope and pathway to achieving zero emissions airport operations by 2040.

9.3.9 This review will consider how to align the GHG Limits and Thresholds with this policy objective. This may include changes to the definition of ‘Airport Operations’.

9.3.10 A report setting out the process and outcomes of this review will be submitted to the Environmental Scrutiny Group (ESG) within the three-month timescale. The ESG will review this submission (involving the GHG Technical Panel where needed) and respond in writing within one month of submission.

9.3.11 Where the review identifies the need for changes to the GHG Limits or Thresholds, these will be taken forward using the process set out in paragraph 24(3) of Schedule 2 to the **Draft DCO [REP5-003].**

9.3.12 In that context the Applicant believes that the likelihood of achieving the 2040 zero emissions airport target is strong.

9.4 Application of the ‘Luton Net Zero: Climate Policy and Action Plan’ [REP3-100]

9.4.1 The Applicant confirmed that the Luton Borough Council’s Luton Net Zero: Climate Policy and Action Plan[17]) is part of Luton’s 2040 vision, it is the commitment of LBC to reduce GHG emissions from the Council estate and operations to net zero as well as lead the way to a net zero Luton by 2040.

9.4.2 The scope of this target, Luton and the council estate, does not include, either explicitly or implicitly, the airport.

9.4.3 The airport is mentioned several times in the Plan, including on pg.5, “Growing the airport” which is one of the Luton 2040 objectives.

9.4.4 Section 4 of the Plan focuses on the airport and provides a range of measures to reduce its carbon impact. These measures are entirely consistent with the measures identified within the **Chapter 12** of the **ES [REP3-007]**, and in **Appendix 12.1 Outline GHG Action Plan [APP-081]**.

9.4.5 The Applicant considers, therefore, that the application for development consent is aligned with the Luton Borough Council Luton Net Zero: Climate Policy and Action Plan[18].

9.5 Implications of the Secretaries of State's assessment of the significance of emissions following the decision to approve application ref: 21/00031/VARCON when compared to the increase in emissions from the Proposed Development

9.5.1 It was acknowledged that issues relating to this agenda point would be covered more fully in ISH9 on Green Controlled Growth.

9.5.2 The Applicant noted the measures considered in the P19 application are not as sophisticated as those set out in the Applicant's proposed **GCG Framework [REP5-022]**. The Applicant also noted that paragraph 24 of the decision letter[19] agreed that obligations in the carbon reduction strategy sufficiently meet requirements. The GCG Framework will have carbon reduction targets linked to passenger throughput which will consequentially place a limit on growth.

9.5.3 This effectively echoes the approach taken by the Applicant through the implementation of the **Green Controlled Growth Framework [REP5-022**]

9.6 Emissions other than carbon dioxide

9.6.1 The Applicant recognises the role of non-CO2 effects and discusses this issue in Section 12.12 of **Chapter 12** of the **ES [REP3-007].**

9.6.2 The impact of non-CO2 effects is not quantified or included in the GHG assessment presented in **Chapter 12** of the **ES [REP3-007]** for a number of reasons as explained below.

9.6.3 There remains considerable uncertainty, as recognised by the Department for Transport and the Climate Change Committee, as to the magnitude of the additional warming impact from non-CO2 effects. Jet Zero One Year On page 33 reiterates this and states that, there is a requirement to *"Undertake further work on how non-CO2 impacts could be monitored and included in the UK ETS, in line with our aim to price aviation's non-CO2 climate impact once scientific understanding and consensus permit."*[20]

9.6.4 The UK Government itself cannot agree on a suitable uplift factor to be applied, with different values being offered in the annual dataset of conversion factors[21] (x1.9) and the Jet Zero Strategy[22] (x 3).

9.6.5 Furthermore, these impacts are explicitly excluded from UK carbon budgets, the Climate Change Committee's sectoral budgets, and the Jet Zero Scenario 2 emissions pathway used to contextualise aviation emissions

9.6.6 The Applicant is committed to following all legislation, policy and guidance on this issue as the science and the Applicant's understanding of the impact of non-CO2 effects improves.

9.6.7 **Post hearing Submission**: The extent of uncertainty and the need for further research before confirming how this should be addressed is outlined on page 33 of the Department for Transport's Jet Zero – One Year On report of July 2023 (Ref 22).

10 AGENDA ITEM 9: LANDSCAPE AND VISUAL

10.1 Introduction

10.1.1 In response to an additional query from the ExA the Applicant confirmed that the methodology set out in **[REP4-070]** confirmed that Winch Hill Wood was the closest appropriate Ancient Woodland in relation to tree T343.

10.2 Chiltern Hills Area of Outstanding Natural Beauty (AONB):

Update on the current position, details of the discussion/ consultation held with bodies and summary of feedback provided, current scope of the assessment and timescales for submission

10.2.1 The ExA noted that all designated AONBs in England and Wales were rebranded as 'National Landscapes' on 22 November 2023. The Applicant noted this but confirmed for the purposes of consistency these areas would be referred to as AONB's during the Hearing. Chiltern Conservation Board (CCB) also noted that the legal definition is still AONB.

10.2.2 The ExA was keen for an understanding of the timing for the submission of the Chilterns AONB Special Qualities Assessment, what discussions have been held, summary of feedback, scope of assessment and timescales for submission.

10.2.3 The Applicant outlined the engagement that has taken place with LPAs, NE and CCB.

10.2.4 The Applicant confirmed that a virtual meeting was held with NE, CCB, the Combined Authorities, CBC and LBC on 30 October 2023. The Applicant collated feedback from each stakeholder. Key comments received were the need for the findings of the assessment to align more closely with those of **Chapter 14** of the **ES [AS-079]**; greater consideration of tranquillity as part of the methodology; some 'scoped out' Special Qualities to be scoped back into the assessment; and additional mapping for tranquillity and dark skies to be included.

10.2.5 The Applicant has agreed four additional viewpoints within the AONB to be included in the assessment. The focus of these identified viewpoints is on perceptual qualities and special qualities of the landscape.

10.2.6 The Applicant stated that its intention is to submit an updated draft of the assessment to stakeholders by Deadline 6. The ExA requested that a draft assessment be submitted to the ExA as well by Deadline 6. with a final version to be submitted to the ExA by Deadline 7.

10.2.7 **Action point 42: Submit draft of the assessment on the special qualities of the Chilterns National Landscape with completed report to be submitted at the following deadline.**

10.2.8 The ExA asked if the assessment will consider increase to flights and requested a table be provided in the report of increases of flights in actuals and percentage increase.

10.2.9 The Applicant confirmed that mapping overflight contours are going to be shown in the report. There are two areas of the AONB north and west of Luton, which are overflown and overflight data for each assessment phase can be presented in the report.

10.2.10 **Action point 43: The Applicant to review whether the special qualities assessment report can be accompanied by a table showing baseline overhead flights within the National Landscape compared to increased flights. If possible, this should include both the percentage increase and numerical increase split between different flight paths. In addition, the report should be accompanied by a map showing flightpaths over affected areas.**

10.2.11 The Applicant confirmed that a visual intrusion at day and night from aircraft had not been considered, however please see note below.

10.2.12 **Post hearing submission:** Correction - the visual impact of aircraft movements is considered in the Landscape and Visual assessment reported in **Chapter 14** of the **ES [AS-079]** in the day as described in paragraph 14.3.11 and section 14.9 and night-time as reported in paragraph 14.6.6, limited to brief discussion where required.

10.3 Proposed extension to the AONB, the suitability of the Sensitivity Test [APP-107] and weight to be given to the proposed extension in the assessment of the Proposed Development;

10.3.1 The CCB confirmed that the boundary review project timings have changed. Consultation planned mid 2024 – so will be the first-time documents are in the public domain. CCB confirmed that limited weight should be applied to the extension of AONB project – there is nothing in the public domain therefore it cannot inform the assessment. It was noted that NE are informing the LPAs that may be affected by the extension.

10.3.2 LBC support limited weight to be afforded to extension. The Combined Authorities also support limited weight be given to it.

10.3.3 The Applicant noted the above positions but confirmed its belief that at this moment, no weight should be given. The boundary change plan was at a very early stage akin to the early stages of a Local Plan review.

10.3.4 The ExA noted that the Examination will close on 10 February 2024. The ExA submits its report to the Secretary of State by 10 May. The Secretary of State is anticipated to determine the application is within three months from receipt of the ExA report which indicates a determination date of August 2024.

10.3.5 The ExA asked whether the landscape in the proposed AONB area of search should be considered a 'valued landscape' under paragraph 174 of NPPF (Ref 14) and what weight should be given.

10.3.6 **Action point 46: Provide a written response regarding the application of paragraph 174(a) of the National Planning Policy Framework (NPPF) and whether the landscape that is within the proposed area of search of a possible extension to the Chilterns National Landscape should be considered a 'valued landscape'**

10.3.7 The ExA referred to the Applicant's Chilterns AONB Sensitivity Test [**APP-107]** in particular changes to sensitivity of landscape receptors.

10.3.8 The Applicant reiterated its view that the introduction of a designation to an existing view (in this case extension of AONB status) does not mean that the value of that view is necessarily increased. It is acknowledged that a change in designation is possible but the enjoyment of the view experienced does not change as a result of the designation.

10.3.9 The Applicant also reiterated its view that section 6.37 of the Guidelines for Landscape and Visual Impact Assessment (Landscape Institute, third edition) referred to as 'GLVIA3' did not apply as it relates to current and not potential views. The LVIA original judgements effectively take into account the value of the views that may merit future designation. The views experienced by visual receptors within an area are the same in terms of the composition, character and nature of view and qualities or detractors present.

10.3.10 **Action point 47: Provide a response to Natural England request [REP4-198] to re-evaluate judgements around the 'susceptibility of visual receptors' and the 'value of views' for visual receptors in the Chilterns AONB Sensitivity Test [APP-107]. Confirm whether the existing judgement is to be reconsidered and, if not, explain why**.

10.4 Implications of Section 245 of the Levelling-up and Regeneration Act 2023 (LURA), which will amend Section 85 of the Countryside and Rights of Way Act 2000

10.4.1 **Post hearing submission:** the Applicant has set out below its full legal analysis of this matter, which informed the summary that was conveyed orally at ISH8.

10.4.2 Section 245 of LURA will amend section 85 of the Countryside and Rights of Way Act 2000 (CROW). Currently section 85(1) provides that: "*In exercising or performing any functions in relation to, or so as to affect, land in an area of outstanding natural beauty, a relevant authority shall* ***have regard to*** *the purpose of conserving and enhancing the natural beauty of the area of outstanding natural beauty*".

10.4.3 Effective from 26 December 2023, the relevant provision in England will become section 85(A1) and will read: "*In exercising or performing any functions in relation to, or so as to affect, land in an area of outstanding natural beauty in England, a relevant authority other than a devolved Welsh authority must* ***seek to further*** *the purpose of conserving and enhancing the natural beauty of the area of outstanding natural beauty*".

10.4.4 The Applicant acknowledges that this amendment will strengthen the obligation on "relevant authorities", the definition of which applies to the Secretary of State as decision-maker on the DCO application.

10.4.5 As far as the Applicant is aware, no explanatory notes have yet been published to accompany LURA. Furthermore, the LURA amendments to section 85 will empower the Secretary of State to make regulations about how a relevant authority is to comply with the revised duty under section 85(A1). As such there is limited information at this stage about how the revised duty is intended to be implemented in practice. The following paragraphs set out the Applicant's analysis of the implications.

10.4.6 Whilst strengthening the section 85 duty, the Applicant makes the following observations about the effect of this amendment in the context of a Nationally Significant Infrastructure Project (NSIP) such as the Proposed Development:

a. It is notable that the revised duty is not limited to functions related to planning – the section 85 duty is of general application to all functions (i.e. including those outside of the planning sphere) exercised by a relevant authority in relation to an AONB.

b. This is important because the Applicant considers the LURA amendment to section 85 effectively brings non-planning functions into line with national planning policies which already have the equivalent effect in relation to development affecting AONBs, including the Airports National Policy Statements (ANPS) and the National Planning Policy Framework (NPPF).

c. It should be recognised that the section 85 amendment is not outcome-based. The Applicant's view of the practical application of "seek to further" therefore is that a relevant authority must, when exercising a function, look for opportunities to further the conservation and enhancement of AONBs, insofar as is possible.

d. What is possible must be read in context of the function being exercised. Functions in relation to NSIPs are set out in the Planning Act 2008 (the 2008 Act). That regime permits development which has adverse effects on the natural beauty of AONBs, where the benefits of a proposal outweigh its adverse impacts. Plainly the LURA does not amend these components of the 2008 Act regime. As a matter of statutory interpretation therefore, it should be assumed that Parliament's intent is that the amended section 85 duty can be complied with where an NSIP results in adverse effects in an AONB.

10.4.7 Expanding on the point made under sub-paragraph b. above, paragraph 176 of the NPPF and paragraph 5.219 of the ANPS both provide that "great weight" should be given to conserving and enhancing landscape and scenic beauty in AONBs, which have the "highest status of protection" in relation to these issues. Paragraph 5.222 of the ANPS continues that, for projects outside of an AONB which may affect an AONB, the development should aim to avoid compromising the purposes of designation, and such projects should be designed sensitively given the various siting, operational, and other relevant constraints.

10.4.8 Taking these policies as a whole, the Applicant's conclusion is that they have a combined effect and outcome that is consistent with the LURA amendment to section 85 of CROW.

10.4.9 It follows that, in the Applicant's view, the LURA amendment has no material effect on the existing assessments contained in its Environmental Statement and Planning Statement, nor on the Applicant's substantive case for development consent. As regards AONB impacts, the Applicant highlights that: the Proposed Development does not involve any development within the Chilterns AONB; significant effects are predicted for assessment Phase 2b, but only from aircraft noise; the Applicant has sought to mitigate these noise effects as far as practicable through GCG and other noise measures; aircraft noise in the AONB is also a function of airspace management, which is not within the Applicant's gift. It is not possible to mitigate noise effects any further at the scale of development proposed, and nothing further can reasonably be done by the Applicant in terms of conserving and enhancing the Chilterns AONB.

10.5 Visual effects and approach to mitigation

Visual effects from buildings and structures on the eastern edge of the development, the fire training ground (Work No. 2d) and the appropriateness of new planting at mitigating effects including in winter

10.5.1 The Applicant confirmed that alternative locations for the new Fire Training Ground (FTG) were considered. The FTG must be located airside, and it must be located away from the runway and away from other buildings.

10.5.2 The visualisations provided (and the visual assessment carried out) are based on a Rochdale Envelope (i.e. consider the maximum physical extent of the Proposed Development).

10.5.3 It is not considered appropriate to provide detailed visual representations of the FTG as the detailed design, layout and type of activities are not defined at this stage, however it is anticipated that the proposed FTG will be similar in size and scale to the existing facility.

10.5.4 The Applicant confirmed that all of the new planting proposed is considered appropriate to mitigate the significant landscape and visual effects identified. Not all of the Proposed Development can be screened from areas to the east and south but where it is visible it will be mainly seen in the context of the existing airport development.

10.5.5 The Applicant has still to carry out detailed design.

10.5.6 It was noted by the ExA that the effect of smoke/flames resulting from fire training exercises is short lived.

10.6 Lighting Assessment:

Whether the Lighting Obtrusion Assessment [APP-052] and [APP-053] adequately identifies likely significant effects and the need or otherwise for a night-time Landscape and Visual Impact Assessment

10.6.1 The Applicant's lighting expert was not available and so the ExA agreed that this issue will be rolled over in to the second round of written questions.

10.6.2 **Action point 51: Respond to questions on lighting to be asked as written questions as the Applicant's lighting expert was not available (see table below).**

10.6.3 **Action point 52: Applicant to watch the live stream of the section that deals with concerns regarding lighting and respond to the points made by the Interested Parties on these matters.**

11 AGENDA ITEM 10: DESIGN

11.1.1 The ExA asked questions on the following subjects:

a. suitability of the update to the **Design Principles [REP5-034]** and the **Applicant's Response to Issue Specific Hearing 6, Action 33: Principles of Good Design [REP5-043]** submitted at Deadline 5;

b. discussion on the site layout, parameters and the components of the Proposed Development and extent of primary mitigation measures explored; and

c. need for masterplan and/or design code to further inform the detailed design stage.

11.1.2 The various issues were effectively considered together.

11.1.3 The purpose of the **Design Principles [REP5-034]** is stated in the updated document issued at Deadline 5 **[REP5-034]** and was also outlined at ISH 6 **[REP4-070]**. The purpose is to allow future designers to incorporate design standards, design parameters and commitments to stakeholders, ensuring the Proposed Development delivers 'good design'.

11.1.4 The ExA acknowledged the response provided by the Applicant in response to question PED.1.2 **[REP4-061).** The Applicant's position remains that an illustrative masterplan was submitted with the application for development consent in the form of the **Scheme Layout Plans [AS-072]**. The operator's previous masterplan only considered a growth scenario to 18 mppa (modified to 19 mppa by the recent P19 planning permission).

11.1.5 The assessment Phase 2b Scheme Layout Plans [**AS-072**] is therefore the 32 mppa masterplan. It is the intention to "certify" the scheme layout plans in the

DCO to allow the progressive discharge of "parts" of the scheme as identified and described against the masterplan to which they are drawn from.

11.1.6 The Applicant stated that issues relating to the need for a masterplan, discussions on site layout and parameters as well as any need for a design code to inform the detailed design stage can properly be considered at ISH10 on the Draft DCO.

11.1.7 The Applicant explained that the principal witness for the Applicant on whether a Design Code or Design Panel was required to inform the detailed design stage would not be available on Friday and that it may assist the ExA if he could speak now in relation as to reasons why the Applicant did not think that a Design Panel or Design Code was necessary for the Proposed Development.

11.1.8 The **Design Principles [REP5-034]** have been developed to secure 'good design' at the detailed design stage and were updated at Deadline 5 in response to feedback.

11.1.9 The provisions of Requirement 5 of the **Draft DCO [REP5-003]** have also been strengthened in respect of detailed design requirements. The Scheme Layout Plans are also for certification within the DCO and show the masterplan for the airport up to 32 mppa as outlined above.

11.1.10 Independent design review is referenced as one of several tools for securing 'good design' in the NPPF but is not referenced in the Airports National Policy Statement (ANPS)[23]. The ANPS encourages independent design advice (as taken by the Applicant) to embed 'good design' principles into the Proposed Development.

11.1.11 The Applicant has reviewed other DCO projects and identified very few (A303 Amesbury to Berwick Down and North Lincolnshire Green Energy Park) that include an independent design review process.

11.1.12 At this stage the Applicant does not think independent design review is appropriate in this instance because the Proposed Development is a highly complex long-term programme of development with many interdependencies between the principal components and with many aspects of the design defined by international standards.

11.1.13 The external appearance of the proposed terminal is clearly an important consideration, but it cannot be wholly separated from the internal configuration of the building which needs to meet a wide range of operational and stakeholder requirements. Detailed design will require extensive engagement with a wide range of stakeholders and co-ordination across a range of different design and technical teams. To take just security for example this would include Department for Transport (security); Centre for Protection of National Infrastructure (landside security); UK Border Force (immigration); His Majesty's Revenue and Customs; and Bedfordshire Police.

11.1.14 A process of independent design review would add significant further complexity to this design and consenting process. There is a risk that comments from a design review panel that doesn't fully appreciate how these requirements drive the internal configuration and how this influences the external appearance could cause confusion at the detailed design stage. This could create programme delays and other risks to the delivery of the project.

11.1.15 Some other complex projects and infrastructure programmes have created their own Design Review Panel to manage these issues. Examples include the London Olympics, the NHS Design Review Panel and High Speed 2.

11.1.16 In this case, the Applicant believes that, as with other DCOs, Requirement 5 and the **Design Principles [REP5-034]** are an appropriate approach to securing good design.

11.1.17 **Action 53: The Design Principles [REP5-034]** remains 'live' and the Applicant is engaging with the Host Authorities and other stakeholders to further refine these principles and to consider the merits of a design review process or other mechanism(s) to secure good design as per ISH 8 Action Point 53.

12 AGENDA ITEM 11: HERITAGE

12.1.1 Matters relating to Heritage were not discussed and issues will be raised in the next round of Written Questions.

13 AGENDA ITEM 12: ANY OTHER MATTERS

13.1.1 15.1.1 The Applicant had no further comments.

14 AGENDA ITEM 13: ACTION POINTS

14.1.1 The Action Points noted by the ExA were made available on 1 December 2023 and have been noted in Table 1.1.

15 AGENDA ITEM 14: ANY OTHER BUSINESS

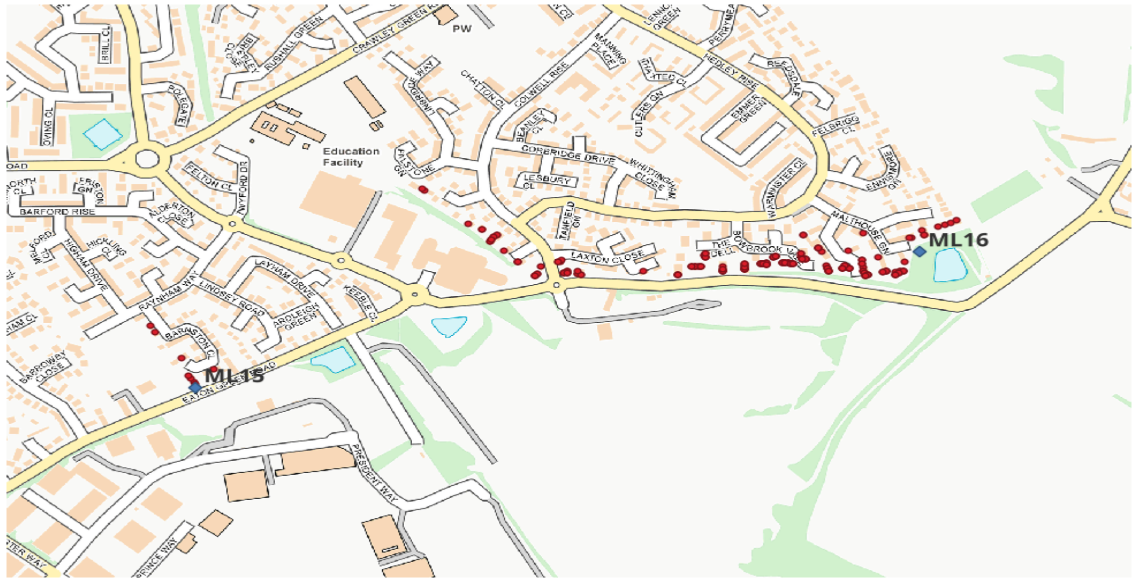
15.1.1 The Applicant had no further comments.

Table 1.1: Applicant's Response to ISH8 Action Points (NB: Any missing action below was addressed to another third party)

Action	Description	When	Applicant's response
Noise and Vibration			
1	To review the effect of impact piling if it were to occur and whether it needs to be assessed in the Environmental Statement (ES)	D6	As was noted in the hearing, regardless of construction methods used in the past for other projects, it is not proposed that impact piling would take place as part of construction of the Proposed Development. It is therefore considered that an appropriate assessment of the likely significant effects of construction has already been undertaken and therefore impact piling does not need to be assessed in the ES. As no impact piling is proposed, it is not possible to provide an assessment of its effect as there are no proposals (location, duration etc) that can be used to undertake such an assessment. There is always some degree of uncertainty in construction noise assessments which is why the controls within the CoCP require that: **a.** Best Practicable Means (BPM) are employed, which requires the selection of quiet and low vibration equipment and a review of the construction programme and methodology to consider quieter methods (see paragraph 14.2.2a of the CoCP). Such considerations would mean the selection of impact piling is highly unlikely; **b.** Where construction activities that are noisy or could generate perceptible vibration at any sensitive receptor are required to be undertaken, the lead contractor will seek to obtain consent from the relevant local authority under s61 of the Control of Pollution Act 1974 (see paragraph 14.2.10 of the CoCP). Such an application must include site specific noise management and mitigation measures; **c.** In the unlikely event that impact piling were proposed, it cannot take place without an impact piling method statement, including measures to control noise and vibration, being submitted and approved by the local authority as part of the s61 consent process; **d.** In the unlikely event that noise levels forecast in a s61 application exceed the relevant Significant Observed Adverse Effect Level (SOAEL) defined on the ES (due to impact piling or otherwise) and the criteria in 14.2.2c of the CoCP, a scheme of noise insulation will be set out in the Section 61 consent application to avoid the significant adverse effects on health and quality of life that would otherwise result (see paragraph 14.2.2c of the CoCP); and **e.** In the unlikely event that vibration levels forecast in a Section 61 application exceed the relevant SOAEL defined in the ES (due to impact piling or otherwise) the lead contractor will undertake a detailed construction vibration assessment as part of a Section 61 application and, if required, identify measures to avoid significant adverse effects on health and quality of life (see paragraph 14.3.5 of the CoCP). A comparison of how noise from impact piling may differ from Continuous Flight Auger (CFA) or sheet piling (vibro or hydraulically driven) is provided for additional information. It is likely that piling would either be CFA or sheet piling (vibro or hydraulically driven), with the assumption that CFA piles would be used for buildings made in accordance with Appendix 17.6 [APP-126]. Construction noise predictions for CFA or sheet piling (vibro or hydraulically driven) were undertaken in Chapter 16 of the ES [AS-080]. Sound power data used in construction noise predictions are presented in Appendix 16.1 [AS-096]. For sheet piling, a sound power level of 116 dB was applied in predictions whereas, for CFA piling, a combined sound power level of 114 dB (for the rig, compressor and crane) was applied. Table C.3 of BS 5228-1:2009+A1:2014[24] provides sound data for piling plant. The highest provided level of noise from an impact driving rig is 89 dB at 10 m for pre-cast concrete piling, which is

Action	Description	When	Applicant's response
			equivalent to a sound power level of 117 dB. This is 1 dB higher than sheet piling noise predictions and 3 dB higher than CFA piling predictions assumed in the ES. As per Table 7.3 of [AS-082], piling would only be required in Phase 2. The highest level of noise predicted from all construction activities is 67 dB LAeq,T at GR16 (Table 5.6 of Appendix 16.1 [AS-096]). This noise level is calculated from activities during stage 2-3 (Table 5.2 of Appendix 16.1 [AS-096]) and covers noise from the following activities: **a.** Airport Access Road – east section works **b.** Airport Access Road – west section works **c.** P10 and P11 car park construction **d.** Luton DART extension **e.** Terminal 2 and west pier construction **f.** Effluent Treatment Plant/ Sewage Treatment Plant/ Fuel Farm construction **g.** Apron and stands construction **h.** Alpha taxiway realignment Although impact piling (if required) may result in an increase in noise generated by some of the activities listed above, the overall increase in LAeq,T noise levels is unlikely to be materially different from the construction noise levels presented in Table 5.6 and Table 5.7 of Appendix 16.1 [AS-096] as the total noise level will be a combination of piling and other construction noise sources. Additionally, piling would last for a relatively short period of time in comparison to other construction activities and only influence construction noise levels for limited periods likely to be no longer than a matter of weeks. Consequently, no exceedances of the SOAEL are likely and no additional likely significant effects would be identified in any case because of the protective measures that would be triggered when exceeding SOAEL as set out above.
2	Clarification of why ML15 monitoring data should be applied to all receptors in the night-time noise assessment, rather than ML16 data. Explain how use of ML16 data would affect the results of the assessment.	D6	Figure 3-1 shows locations of sensitive receptors that are predicted to experience noise levels exceeding the Lowest Observed Adverse Effect Level (LOAEL) due to night-time construction works. 88 receptors are identified in the Eaton Green Road area that may experience exceedances of the LOAEL due to night-time construction works. The night-time construction noise LOAEL is set at a fixed level of 45 dB $L_{Aeq,8h}$ (Table 16.11 of **[AS-080]**) and has not been adjusted according to measured ambient noise levels. This is a conservative approach, as the alternative approach (referred to as the ABC method in BS 5228-1) is to adjust (i.e. increase from 45dB$L_{Aeq,8h}$) the LOAEL when the ambient noise levels are higher.

Figure 0-1: Monitoring locations (blue) and sensitive receptors (red) exceeding LOAEL



15.1.2

ML15 was used to provide representative noise data for properties affected as the majority of affected properties are located adjacent to Eaton Green Road and would experience similar levels of ambient noise at night. A summary of measured noise levels and the approximate distance to Eaton Green Road is presented in Table 3-1.

Table 0-1: Summary of Baseline Noise Measurements at Eaton Green Road

Measurement Location	*Approximate Distance to Eaton Green Road*	*Measured $L_{Aeq,8h}$ dB*
ML15	*10 m*	*60*
ML16	*90 m*	*46*

Of the 88 receptor locations identified in Figure 3-1, approximately 51 are within 30 m of Eaton Green Road and therefore ML15 is representative of these receptors. These receptors are predicted to experience night-time construction noise levels of up to 48 dB $L_{Aeq,T}$. Predicted night-time construction noise levels are below ambient noise levels for all these receptors.

35 receptors are located within a distance of 30 and 150 m of Eaton Green Road, with an additional two receptors located at approximately 200m from Eaton Green Road. For these receptors, ML16 may be more representative due to further distance from Eaton Green Road. However, as these receptors are further from the construction site than the receptors adjacent to Eaton Green Road, their predicted construction noise level is also lower at 45-46dB$L_{Aeq,T}$ which does not exceed the measured sound level at ML16.

The conclusions of no likely significant effects from these receptors is therefore as reported in **[REP4-080]** even when using data from ML16 because:

a. the majority of receptors in this community experience predicted construction sound levels that are just above the LOAEL (by up to 3dB) but substantially below the ambient sound level;

b. a smaller proportion of receptors experience predicted construction sound levels equal to, or just below, the ambient sound level, however these receptors are exposed to lower noise levels that are equal to or at most 1dB above the LOAEL.

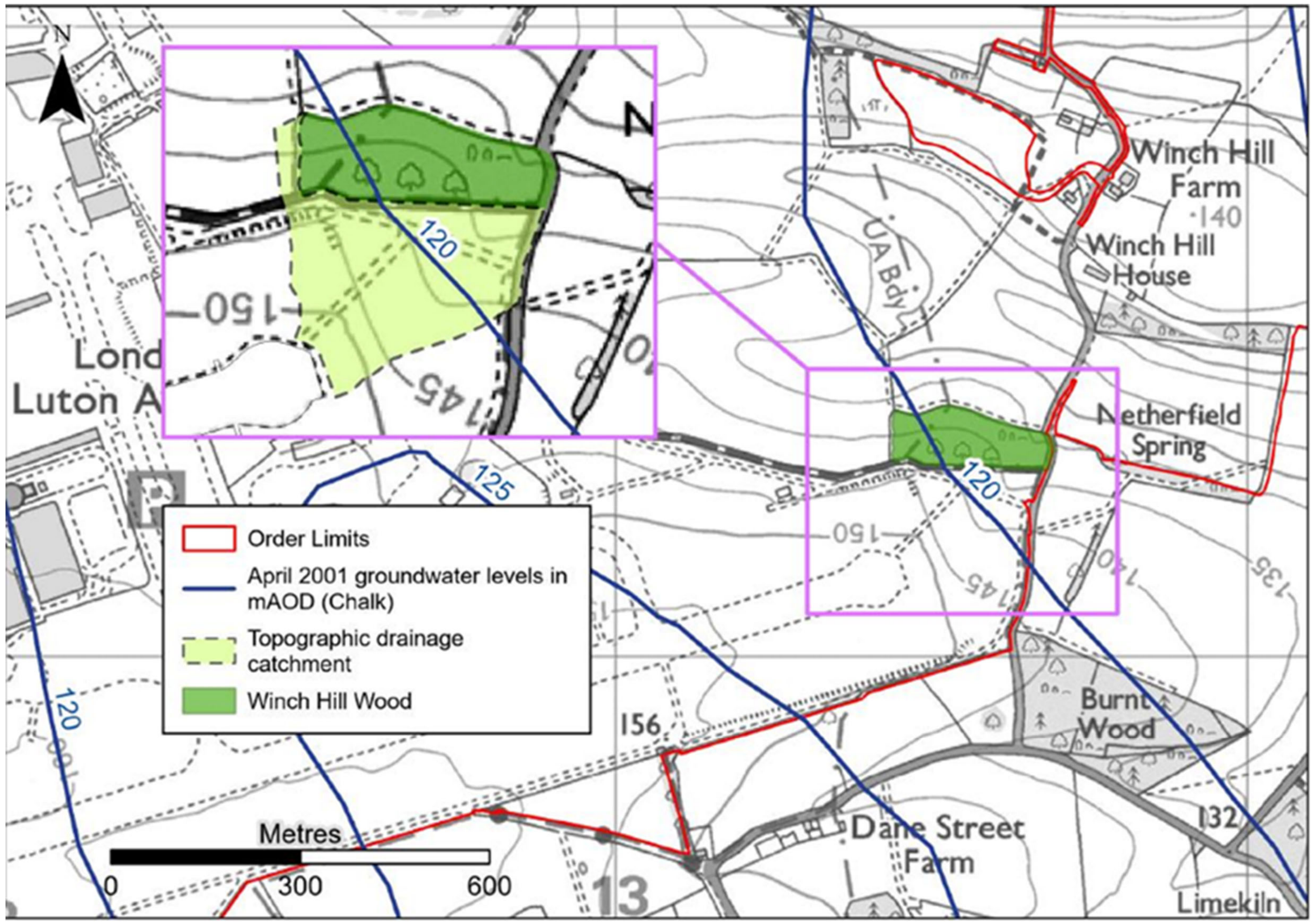
Action	Description	When	Applicant's response
3	In post hearing note, provide reference to noise contour figures that explain eligibility for traffic and ground noise insulation, which would exclude the need to give a list of eligible properties.	D6	For surface access noise, because the eligibility is based on a combination of noise exposure and change, it is not possible to refer to a single figure. However, the number and location of properties that are expected to be eligible are clearly described in paragraph 16.9.232 of **Chapter 16 [REP1-003]**. The final list of eligible properties would be confirmed through the monitoring process described in paragraph 6.1.29 onwards of **Draft Compensation Policies, Measures and Community First [REP4-042]**. For ground noise, the eligibility is based only on noise exposure for the daytime 55dB$L_{Aeq,16h}$ contour and night-time 45dB$L_{Aeq,8h}$ contour and so the extent and location of potential eligibility can be inferred from the ground noise contour figures for each assessment phase (Phase 1: **Figures 16.29** and **16.30** of the **ES [AS-108]**, Phase 2a: **Figures 16.53** and **16.54** of the **ES [AS-111]**, Phase 2b: **Figures 16.77** and **16.78** of the **ES [AS-115]**). Whilst the daytime 55dB$L_{Aeq,16h}$ contour is not plotted in these figures, the extent of the night-time 45dB$L_{Aeq,8h}$ contour is larger and so would include those within the 55dB$L_{Aeq,16h}$ contour. The number of potentially eligible properties for the ground noise insulation scheme is also quantified as 3,800 in Table 4.1 of **[REP4-079]**, though the footnote to that table states this is a "Worst-case estimate based on the noise assessment presented in **Chapter 16** of the Environmental **Statement [REP1-003]**. This assessment is undertaken based on a single reasonable worst-case day (see paragraph 16.6.19 of Chapter 16). Numbers of eligible properties are likely to be lower when eligibility is determined based on actual ground movements and ground noise emissions." The Applicant noted that whilst the figures can be used to infer the extent of eligibility, their purpose is to accompany the noise assessment in the environmental statement and they are not intended to provide the means to identify individual properties nor their eligibility for noise insulation. For the reasons set out above, it would not be appropriate to provide a list of eligible properties at this stage, as final eligibility can only be confirmed through the processes described above and there will be tools available for communicating eligibility that are designed specifically for this purpose.
5	Discuss with operator the geographic extent of the reduction in noise from the use of the full runway length and provide a map showing where this noise reduction could apply.	D6	Whilst the results of the trial are not sufficiently detailed to be able to be reported in a map format, the airport operator has provided the following information: The airport operator conducted a full-length runway take-off trial in February and March 2022 in order to understand the potential noise benefit. All operators of departing aircraft were asked to take off using the full length of the runway rather than using the intersection. During the trial, noise and track data was monitored to produce a recommendation to operators. The airport operator analysed this data in collaboration with LADACAN and found that there was a reduction of approximately 0.5dB in areas of south Luton, however there was negligible difference in noise at the fixed noise monitors at 6.5km from the Airport. As part of the trial, the airport operator modelled the difference in noise this may create for each departure. This results in a reduction in the area of the 57dB $L_{Aeq,16h}$ daytime contour of around 0.3km^2 and a reduction in the area of the 48dB $L_{Aeq,8h}$ night-time contour of around 0.5km^2. A reduction in departure thrust due to the additional runway length could lead to further changes in contour area, but the effect would vary depending on the specific contour. A current challenge with implementing the use of the full runway is that backtracking to the end of the runway introduces delay. However, it should be noted that the extended taxiway links introduced as part of the Proposed Development would remove the need for backtracking to use the full runway length. Hence, there is the potential for some noise improvement as these additional taxiways are delivered in the later phases of the Proposed Development.

Action	Description	When	Applicant's response
8	Submit more detailed comparison table regarding fleetmix (19 mppa permission vs Application)	D6	The requested comparison table is provided in Appendix A to this document.
Health and Community			
10	Revise ES Chapter 13 to remove references to a significant perception effect during operation, consistent with the errata document. In addition, update the document to include the updated future baseline information submitted to the Examination at D4 [REP4-068]. Update of ES to also include any adjustments that would result from Action Points 14 or 15.	D7	Applicant to respond at D7.
13	Submit in writing the comments, including any further follow up comments, made on health. The Applicant to make a written response at D7, including the matter of the errata.	D7	Applicant to respond at D7.
15	Council to explain what the Healthy Airports checklist referred to in its LIR [REP1A-002] does and what additional benefit using the checklist would provide to the assessment of health and community effects. In addition, confirm whether this is something that can be applied retrospectively. Applicant to respond at following deadline.	D7	Applicant to respond at D7.
16	Submit Basner reference that sets out how awakenings have been assessed, or relevant extracts if restricted due to copyright.	D6	The requested paper is provided in Appendix B to this document. The equation used to predict awakenings is equation 2 on page 13 of the research paper.
19	Confirm whether Regulation 21(c) of the Infrastructure Planning (EIA) Regulations 2017 would be engaged by the request from UKHSA for monitoring.	D6	The Applicant confirms that it is not aware of any studies into noise insulation efficacy that are carried out in accordance with any obligation under UK law. As such, it is not considered that the UK HSA's request for such monitoring would engage Reg 21(3)(c) of the IP(EIA) Regs 2017
20	Applicant and UKHSA/ Office of Health and Improvement and Disparities (OHID) to meet to discuss possible health monitoring and an agreed position statement/ way forward	D7	Applicant to respond at D7.
Air quality			
21	Submit a copy of the note prepared by the Applicant on the Hitchin Air Quality Management Area (AQMA). Joint Host Authorities to provide their response to the note.	D6	This has been submitted at Deadline 6 – please refer to the **Applicant's Response to Issue Specific Hearing 8 Action 21 - Hitchin AQMA Impact Assessment Summary Note [TR020001/APP/8.143].**
22	Submit a copy of the Applicant's proposed outline fuel odour control procedure, LBC to provide a response. Discuss a mechanism for LBC to engage with the procedure and explain how the procedure would integrate with any airport environmental management system.	D6	This has been submitted at Deadline 6 – please refer to **Applicant's Response to Issue Specific Hearing 8 Action 22 - Proposed Odour Reporting Process [TR020001/APP/8.142]**. This includes the procedure to be followed by the airport operator with regards to odour complaints. The procedure outlined in the document would be relevant to any odour complaints received, including kerosene/fuel odour. The document confirms that the reporting process will include clear reference on how to report the complaint to LBC. The process is considered an appropriate system to manage odour considering the limited odour complaints in relation to airport related odour and the insignificant odour effects predicted in **Chapter**

Action	Description	When	Applicant's response
			7 of the **ES [AS-076]**. The implementation of the system will be secured by section 2.7.b in **Appendix 7.5 Outline Operational Air Quality Plan [APP-065] of the ES**.
23	Response/ update on the implications of the change request for odour and flies and any discussions with the Environment Agency regarding potential odour controls.	D6	<u>Preferred drainage option</u> Should all foul water and contaminated surface water be discharged to the TW network, then there would be no sources of potential odours as the foul wastewater would be conveyed straight to sewer; the glycol contaminated surface water does not contain odorous compounds. <u>Reserve drainage option</u> If the foul wastewater were to be treated on site, this would be done through aerobic processes which oxidise odorous compounds such as sulphur-based compounds and ammonia. Given the proximity of the proposed treatment plant to the source of wastewater, there would also be insufficient time for the foul wastewater to go septic. There is potential for some odour generation from the sludge handling and storage units of the treatment plant; as part of detailed design, an assessment will be made as part of an Odour Management Plan and any units requiring covers and odour control will be identified and remedied as necessary; this would be undertaken as part of the environmental permit regime. Provision for odour control plant is also included as part of Work No. 4d of the **Draft DCO [REP5-003]**. Flies from wastewater treatment are sometimes experienced as a result of the use of trickling filters. It is not proposed to use these on-site due to their large footprint and insufficient treatment performance, therefore no risks from flies are envisaged. With regards to the contaminated surface water, the Applicant does not expect it to contain any odorous compounds. Treatment of this surface water would be done through physical/chemical processes such as filtration cartridges which are enclosed. <u>Environment Agency (EA) Engagement</u> At this stage, limited discussions have been undertaken with the EA regarding odour controls as these would be identified and outlined in an environmental permit application for the water treatment plant. An environmental permit for a sewage treatment plant usually requires an Odour Management Plan to be developed and accepted by the EA.
25	Update regarding how potential complaints in relation to odour could be made and managed, and how this would be secured. Interested Parties (IPs) to comment on subsequent deadline.	D6/7	Please refer to the Applicant's response to action 22.
Biodiversity			
26	Confirm proximity of Winch Hill Wood to the nearest proposed car park and explain the implications for the assessment of effects if it is closer than the 64m advised at D5.	D6	Assessment phase 2b is considered to represent the worst case air quality impact on Winch Hill Wood, which is the case generally for all airport related sources, but also is the case specifically in regard to car park 10. Car park 10 is proposed to increase capacity in spaces (from approximately 1,150 spaces in assessment Phase 2a to 3,165 spaces in assessment Phase 2b). In context of NOx emissions, assessment phase 2a car park 10 emissions are 149 kg/annum with an increase to 404 kg/annum in

Action	Description	When	Applicant's response
			Phase 2b. Phase 2b has been modelled at 64m away from Winch Hill Wood, reflecting the plans in **Work Plans (Part 4 of 6)** [**AS-015**]. The assessment Phase 2a air quality assessment has modelled Car Park 10 at 64m away from Winch Hill Wood, assuming the same area as in Phase 2b (shown in **Figure 7.35** of the **ES** [**AS-100]**). This does not reflect the plan in Work Plans (Part 4 of 6) [**AS-015**], as pointed out by the ExA, which is shown to be approximately 35m from Winch Hill in Phase 2a (as depicted in Work Plans (Part 4 of 6) [**AS-015**], sheet 8, Work No. 4p (02)). However, with consideration of the conservative nature of the air quality assessment and the small contribution that car parks make to the total concentrations at the woodland, the area modelled for car park 10 in assessment Phase 2a is not expected to have any significant implications on the air quality effects at Winch Hill Wood and therefore not expected to materially change the conclusions. In summary, the assessment Phase 2b air quality modelling reflects the permanent car park 10 configuration and provides the worst case assessment of impacts at Winch Hill Wood. During the final assessment Phase 2b stage, the stand-off distances to proposed works in relation to Winch Hill Wood Ancient Woodland is greater than 15m, which is the current Government recommended buffer zone[25]. The permanent car park in assessment Phase 2b lies approximately 64m from the edge of the woodland and the County Wildlife Site/Local Wildlife Site, with a larger distance to the edge of the classified area of Ancient Woodland which does not fully extend to the western edge of the woodland block. Although some works, such as the temporary car park in assessment Phase 2a, utilities corridors and other earthworks will be closer than the 64m permanent car park in assessment Phase 2b, all earthworks will be greater than 15m from the woodland edge, which as stated above, is the current 15m government recommended buffer. Potential effects that these buffers are intended to prevent are either not significant and/or are appropriately mitigated for, such as the air quality effects discussed above and hydrological effects discussed in response to Action Points 27 and 28 below. The root protection zones of the trees along the edge of the Ancient Woodland are assessed and protected within the **Arboricultural Impact Assessment [AS-085]** and ensure avoidance of damage and soil compaction of the root zone of the woodland trees. Indirect effects such as from dust, noise and pollution are appropriately mitigated through the measures within the **CoCP [REP4-011].** Please refer to the Applicant's response to Action Point 27 below for an overview of hydrological effects on Winch Hill Wood. In addition, the Proposed Development will introduce a 50-year management plan for Winch Hill Wood (for details please refer to the **Outline LBMP [AS-029])** which will improve the quality of the woodland vegetation and its general resilience to nitrogen deposition and other negative influences. This is implemented from assessment Phase 1, almost 10 years prior to assessment Phase 2a, and therefore will already be showing positive results from the enhancement and management changes to the woodland.
27	Confirm the extent of likely topographical changes in proximity to Winch Hill Wood. Provide a more detailed assessment of the effects of this on the hydrology	D6	The Applicant's response to ISH6 Action Point 6 **[REP4-070]** outlined that Winch Hill Wood is not considered to be dependent on groundwater as the water table is at several metres' depth (i.e. below the main root zone). This is also supported by the surveyed National Vegetation Classification (NVC) communities for Winch Hill Wood (W8 and W10) as set out in **Appendix 8.1 Ecological Baseline Report** of the **ES [AS-033]** which are not considered to be groundwater dependent features.

Action	Description	When	Applicant's response
	beneath the Woodland and the potential effects of this, or explain why this is not required.		Water supply to the woodland is expected to be principally from rainfall and runoff on the site and the upgradient topographic catchment. The Applicant's response to ISH6 Action Point 6 noted that limited earthworks are located in the upgradient catchment that is considered to feed Winch Hill Wood. A sketch showing the Winch Hill Wood with upgradient topographic surface water catchment area, ground level contours and maximum groundwater level contours is provided below. Landform changes are anticipated at Phase 2a and Phase 2b to the west and north of the woodland, so that the woodland will be at a higher elevation relative to the surrounding landscape, as shown in General Arrangement Drawings (Part 1 of 3) **[AS-018]**. These changes do not impact the catchment feeding the woodland (see Figure below), which is the source of water supply to the woodland, the reduction in elevation may change drainage off the woodland and potentially this change in topography could result in a reduced moisture content in the near-surface soil underlying the woodland. However, the distance from the woodland to the top of the slope, together with the existing topographical fall towards the dry valley means that the changes in landform are not expected to result in a significant change to the woodland water balance.



Action	Description	When	Applicant's response
28	Review whether any other sensitive sites should also be considered in terms of the potential impacts of significant topographical changes on hydrology.	D6	As per the Applicant's response to ISH6 Action Point 6 **[REP4-070]** there are no sensitive sites within the study area that are considered likely to be dependent on groundwater. As such potential impacts from the topographical changes would be limited to impacts from changing surface water/near surface water catchments. Due to the proximity and topography of other sensitive sites relative to the proposed landform changes, the surface water catchments for these sites are not anticipated to be altered sufficiently to result in significant effects.
29	If Actions 26, 27 and 28 result in changes to the assessment of environmental effects, re-visit the assessment of cumulative assessments on these sites.	D7	Applicant to respond at D7.
30	It has been confirmed that all protected woodland and trees have a buffer zone of at least 15m. However, Natural England guidance and IP representations recommend that this is a minimum and may need to be extended depending on the circumstances. Provide	D6	The Applicant has committed to a minimum buffer zone of at least 15m following standing advice from Natural England and the Forestry Commission. As stated within the **Applicant's Comments on Responses to Written Questions by Interested Parties [REP5-052]**, an assessment on Ancient Woodland has been undertaken using this buffer and concluded no significant effects. Therefore, the Applicant considers that this buffer distance does not need to be extended as it adequately mitigates effects.

Action	Description	When	Applicant's response
	further justification regarding the extent of buffer zones around woodland and protected trees.		In addition to the Ancient Woodland, one Tree Preservation Order (TPO) (T703), five ancient (T773, T163, T168, T740, T1310), two ancient and veteran (T174, T343), two veteran (T173, T63) and one group of five ancient and veteran (G156) trees are present within the Main Application Site. The location of these trees is shown within the Arboricultural Impact Assessment which forms **Appendix 14.3** of the **ES [AS-085]**. The below table shows the approximate distances of all protected trees from any earthworks. No other activities likely to damage or impact these trees will occur outside of these earthworks.

Tree Number as shown in [AS-085]	Justification for protection	Approximate distance from earthworks		
		Phase 1	Phase 2a	Phase 2b
T773	Ancient tree	Over 100m from earthworks	Over 100m from earthworks	Over 100m from earthworks
T163	Ancient tree	Over 100m from earthworks	Over 100m from earthworks	Over 100m from earthworks
T168	Ancient tree	Over 100m from earthworks	Over 100m from earthworks	Over 100m from earthworks
T740	Ancient tree	Over 100m from earthworks	Over 100m from earthworks	Over 100m from earthworks
T1310	Ancient tree	Over 100m from earthworks	Over 50m from earthworks	Over 50m from earthworks
T174	Ancient and veteran tree	Over 100m from earthworks	40m from any earthworks	40m from any earthworks
T343	Ancient and veteran tree	25m from any earthworks	Translocated	Translocated
T173	Veteran tree	Over 100m from earthworks	Over 50m from earthworks	Over 50m from earthworks
T63	Veteran tree	Over 100m from earthworks	Over 100m from earthworks	Over 100m from earthworks
G156	Ancient and veteran tree	Over 100m from earthworks	Over 100m from earthworks	Over 100m from earthworks
T703	Tree Preservation Order	100m from any earthworks	100m from any earthworks	100m from any earthworks

Action	Description	When	Applicant's response
			As demonstrated by this table the 15m buffer zone is always exceeded.
31	Confirm whether a location for the relocation of tree T343 has been identified and, if not, whether this is something that could be secured in the draft DCO.	D6	A specific location has not been agreed at this stage, as this would be determined at detailed design. However, the intended location is for it to be within or on margin of Winch Hill Wood and the Applicant will prepare a suitable location as part of committed woodland management practices as detailed in the **Outline Landscape and Biodiversity Management Plan Appendix 8.2 of the ES [AS-029]** in the years preceding the translocation exercise.
Water			
33	Review the proposed changes to the landform upgradient of the infiltration tanks and describe how this might affect groundwater levels, including whether there would be any implications for the risk of flooding.	D6	The understanding of the existing groundwater level and flow regime within the chalk aquifer is document within the **Hydrogeological Characterisation Report [REP4-029].** The Proposed Development includes earthworks which will alter the landform; increasing the elevation in some areas and reducing the elevation in others. The changes in landform at assessment Phases 1, 2a and 2b are shown in the **General Arrangement Drawings (Part 1 of 3) [AS-018]**. Changes to landform can impact groundwater levels by altering infiltration rates (such as changing the permeability or the unsaturated thickness), surface runoff and near-surface flowpaths. The site will be largely covered by low permeability or impermeable surfaces which will reduce infiltration and increase surface water runoff. It is noted that the interfluves which cover the majority of the area upgradient of the tanks are clay covered in the current situation. This runoff will be captured by the drainage system, attenuated (to greenfield runoff rates) and either used by the airport or discharged to ground (assuming clean water). Decommissioning of the existing central soakaway is likely to remove the existing mounding, which is likely to locally lower the water table at the central soakaway location. To mitigate any downstream impacts (such as flood risk) from the new soakaways, the drainage design incorporates a number of measures which are secured by the drainage **Design Principles [REP5-034]**. These measures include rainwater harvesting and reuse (source control), attenuation (pathway control) and infiltration assessments to ensure mounding does not result in downgradient flooding. This will be informed by ongoing monitoring (secured by the design principles).
Land-use			
34	Clarify whether Best and Most Versatile (BMV) land was a factor when optioneering the land requirements. If not, confirm whether it should have been and if this would have resulted in a different outcome.	D6	A summary of the alternatives considered, and options considered during design development in provided in **Chapter 3 Alternatives and Design Evolution [AS-026**] of the **ES**. Further detail is provided in the **Design and Access Statement [AS-049**] and the Sift Reports which are appended to that document [**APP-209 to APP-212]**. The appraisal method applied to early sift stages was based on relevant and accepted options appraisal methodology in reference documents for aviation development at similar early strategic option stages available at that time including: • Airport commission Appraisal Framework, April 2014[26]; • Airports Commission Guidance Document 02 – Long Term Capacity Options: Sift Criteria, May 2013[27]; and • Department for Transport (DfT) WebTAG Unit A5-2 aviation appraisal, December 2015[28]. At the early strategic option level BMV agricultural land was not considered a key deciding factor in line with the appraisal methodologies referred to above, when considering other key environmental factors such as biodiversity, historic environment, noise, water, greenhouse gases, landscape and air quality for example.

Action	Description	When	Applicant's response
			Given the general information on Agricultural Land Classification (ALC) - Provisional (England)[29] available at this early stage all agricultural land around the airport is identified as Grade 3, and BMV land (Grade 3a and above) could therefore not be considered or be a deciding factor in option selection. More detailed mapping of ALC for some areas [**APP-055**] was considered at Sift 2 with BMV agricultural land considered as secondary or sub-criteria under Landscape and Visual Impact and Environmental Land Use (S14) as criteria became more refined, as described sections 2 and 3 of the Sift 2 Report [**APP-210**] and reported in section 5 and Table 5.14. The irregular pattern of Grade 3a (BMV) and 3b (not BMV) to the east of the airport meant that, for options to develop in that area, BMV agricultural land could be and was considered in the appraisal but did not show any difference between the options as all would result in similar impacts at the high level used during option appraisals. Option 2 was appraised as likely to result in greater areas of BMV agricultural land being lost to the south of the airport. BMV land was also considered in Sift 3 in the same way. The Applicant therefore believes that the appraisal framework and criteria used were robust, and in line with accepted methodologies employed for aviation development in the UK. ALC, BMV land and soils were considered appropriately as a sub-criteria to LVIA and land use during the optioneering stages and, although they may not be a key deciding factor, did contribute to the outcome of the options appraisals undertaken.
35	Explain how retention of Wigmore Valley Park would have resulted in a greater loss of BMV land.	D6	Option 1d (shown below as taken from **Design and Access Statement Appendix B Part 3 of 4 [APP-211])** was developed following feedback from consultation, which sought to develop an option which retained Wigmore Valley Park. Option 2 was already considered and appraised at Sift 2 which proposed the new terminal to south of the runway (impacting greater areas of BMV agricultural land) however operational requirements still needed some development within the park. Retaining the Park meant that the new apron would have to connect to existing and be constructed to the east of the retained park over the Luton boundary into Hertfordshire and the Green Belt. The new terminal would then be constructed further to the east, with ancillary buildings and car parks even further into agricultural land extending east. This option would place more new infrastructure in agricultural land and therefore more permanent loss of BMV land and soils, whereas options taking some areas of the Park meant that less agricultural land was permanently lost and the areas to the east would remain in place even though subject to change of use to open space, pastoral agriculture rather than arable, or ecological habitat. As well as being impractical for airport operation and resulting in other greater environmental impacts as reported in [**APP-211**].

Action	Description	When	Applicant's response
			
36	[REP4-070] advises that the area set aside for replacement park in the Green Horizons Park permission was required for excavation of material to construct the aviation platform. This was considered environmentally preferable to importing material. However, the overall environmental impact is also a function of the effects on BMV land. Please confirm if this factor was considered as part of the balance in this case.	D6	As described above in response to Action point 34, BMV land was not specifically considered in early strategic option appraisal in line with appraisal framework and criteria accepted for aviation development in the UK,and would not have influenced the decision making process at that stage. BMV Agricultural land loss was considered as secondary or sub-criteria under Landscape and Visual Impact and Environmental Land Use (S14) as criteria became more refined, as described sections 2 and 3 of the Sift 2 Report [APP-210] and reported in section 5 and Table 5.14, and considered in Sift 3 [APP-210]. The loss of BMV land in this excavated area, was therefore considered in the overall balance and environmental consideration given during option selection. The Environmental Impact Assessment for the Proposed Development also considers the impacts on BMV agricultural land and reported the assessed effects in **Chapter 6** of the **ES [APP-033]** so the effects can be considered in the planning balance.
Climate change and Greenhouse gas emissions			
37	Provide a copy of the Government's update 'Jet Zero Strategy: One Year On' (July 2023) with signposting to	D6	A copy of the Jet Zero Strategy: One Year On is appended to this document for reference. The Government's intention is to continue to tighten up controls on flights not currently covered by the UK

Action	Description	When	Applicant's response
	the sections referred to by the Applicant regarding likely future evolution of policy.		ETS, including the CORSIA scheme. This is set out on page 29 of the Jet Zero Strategy: One Year On document (Ref 16).
41	Provide a full response to the suggestion that there are methods available to assess the effects of non-carbon dioxide emissions by NEF, including those at D3 [REP3-131]. If there is no proposal to use these methods, please explain why not.	D7	Applicant to respond at D7.
Landscape and visual			
42	Submit draft of the assessment on the special qualities of the Chilterns National Landscape with completed report to be submitted at the following deadline.	D6/D7	Please refer to the **Applicant's Response to ISH8 Action 42: Draft Chilterns Area of Outstanding Natural Beauty Special Qualities Assessment [TR020001/APP/8.144]**, submitted at Deadline 6.
43	Review whether the special qualities assessment report can be accompanied by a table showing baseline overhead flights within the National Landscape compared to increased flights. If possible, this should include both the percentage increase and numerical increase split between different flight paths. In addition, the report to be accompanied by a map showing flightpaths over affected areas.	Review by D6/ Table and map if to be provided D7	The Applicant has reviewed the data used in the preparation of the overflight contours shown in **Figures 14.14 to 14.17 of the ES [REP4-037]**. A table showing baseline overhead flights within the AONB (National Landscape) and the increase at each of the assessment phases at relevant locations will be prepared and compiled in the Special Qualities Assessment to be submitted at Deadline 7, a placeholder has been included in the draft provided at Deadline 6 **[TR020001/APP/8.144]** to indicate possible location and content. Maps showing flightpaths are provided as Figure 6.28 of the **Need Case [AS-125]** as is information on split of aircraft between each. However, of more relevance, a figure will be provided showing the locations for which numbers are provided in the table requested and the contours which show the areas affected by overflights. to be submitted at Deadline 7.
46	Provide a written response regarding the application of paragraph 174(a) of the National Planning Policy Framework (NPPF) and whether the landscape that is within the proposed area of search of a possible extension to the Chilterns National Landscape should be considered a 'valued landscape'	D6	Paragraph 174(a) of the NPPF requires policies and decisions to afford protection to *"valued landscapes, sites of biodiversity or geological value and soils (in a manner commensurate with their statutory status or identified quality in the development plan)".* The potential AONB extension area does not have any statutory planning status and is not considered by the Applicant to be a 'valued landscape' in planning policy terms.
47	Provide a response to Natural England request [REP4-198] to re-evaluate judgements around the 'susceptibility of visual receptors' and the 'value of views' for visual receptors in the Chilterns AONB Sensitivity Test [APP-107]. Confirm whether the existing judgement is to be reconsidered and, if not, explain why.	D6	The theoretical introduction of a designation to an existing view (in this case extension of AONB/National Landscape status) does not mean that the value of that view is necessarily increased. It is acknowledged that a change in designation is possible but the enjoyment of the view experienced does not change as a result of the designation. With regards to section 6.37 of GLVIA3[30] it is the Applicant's view that this does not apply as it relates to current and not potential views. Further, with regards recognition of value of the views in question there is no current recording of these views in guide books, tourist maps or facilities to aid their enjoyment and the Applicant is not aware of any references in literature or art as referred to by the Landscape Adviser to the Hertfordshire Authorities. The Applicant's position is that no weight should be given to the theoretical designation of this area and for that reason the Applicant does not believe it is relevant to re-evaluate these judgements accordingly. Susceptibility of visual receptors will remain as per the current situation, affording views across the airport and Luton.

Action	Description	When	Applicant's response
			Paragraph 5.46 of GLVIA 3 confirms that: '*An internationally, nationally or locally valued landscape does not automatically, by definition, have high susceptibility to all types of change'*. The LVIA original judgements effectively take into account the value of the views that may merit future designation. The views experienced by visual receptors within the area will be the same in terms of the composition, character and nature of view and qualities or detractors present.
49	If possible, provide a video of the fire training ground in operation that could be made available to Mr Prosser (Central Bedfordshire Council) to enable an understanding of the visual effects of a fire training event.	D7	Applicant to respond at D7.
50	Joint Host Authorities to provide further detail on the clarity they are seeking regarding the reporting of winter screening set out in Appendix 14.5 of the ES [AS-139]. Applicant to respond at following deadline.	D6/D7	Applicant to respond at D7.
51	Respond to questions on lighting to be asked as written questions as the Applicant's lighting expert was not available (see table below).	D7	Applicant to respond at D7.
52	Applicant to watch the live stream of the section that deals with concerns regarding lighting and respond to the points made by the Interested Parties on these matters.	D6	A Light Obtrusion Assessment (LOA, **Appendix 5.2 of the ES [APP-052 and APP-053])** in accordance with the Institution of Lighting Professionals guidance[31] was prepared to provide a robust, accurate, modelled, quantified and mapped analysis of predicted light levels associated with proposed lighting strategy (appended to the **LOA [APP-053]**) for the Proposed Development and an assessment of the potential obtrusion of any change in light levels such as loss of dark night skies and views of the stars, perception of an unsatisfactory nocturnal environment, and the harming of wildlife habitats. The guidance followed for this assessment is the most authoritative, widely recognised and adopted best practice for the minimisation of light obtrusion. The lighting analysis and assessment was then be used by any other relevant environmental aspect to inform their assessment where lighting levels are relevant to their assessment methodology including landscape and visual, biodiversity, and heritage. This approach was agreed through EIA scoping (ID 3.2.11 of **[APP-047]**) and engagement with the LVIA working group (including all Host Authorities) as described in section 14.5 of **Chapter 14** of the **ES [AS-079]** and endorsed by the landscape representative for the Hertfordshire Authorities at ISH8 (31:23 of Part 5 of recording **[EV15-011]**). The photography provided and used in the LOA is not intended to be compliant with any guidance regarding landscape (such as GLVIA 3) and does not claim such compliance or intended to be considered such. It is High Dynamic Range (HDR) photography produced from the same viewpoints as identified and employed in the LVIA to characterise the luminance profile of the external nocturnal scene. HDR imaging was used to reproduce a greater dynamic range of luminosity than was possible with standard digital imaging or photographic techniques. HDR images can be digitised, calibrated and interrogated for luminance information. This technique is ideal for nocturnal photography, where high levels of contrast are often experienced, and for capturing the nocturnal luminance profile of the scene. The HDR images are created using specialist lighting software (Radiance). The objective of these luminance profile images is therefore to provide quantified luminance data representing the baseline situation that can be compared against 3D simulations of the proposed

Action	Description	When	Applicant's response
			lighting in the Main Application Site when viewed from those locations, not to provide accurate visual representations and they should not be taken as such. The conclusions of the LOA have been considered in the LVIA, which is an acceptable approach as described above. In section 14.6 of **Chapter 14 of the ES [AS-079]** paragraph 14.6.6 states "*In accordance with the findings set out in the Light Obtrusion Assessment provided as Appendix 5.2 of this ES [TR020001/APP/5.02], it is assumed that the predicted impact of sitewide construction and operational lighting to be delivered by the Proposed Development on views from the surrounding area would be* ***negligible****. It is understood additionally that, in comparison to sitewide lighting, the transient and dynamic impact of lower powered vehicular headlights and/or aircraft lights would not have a significant impact on dark skies.*" As reported in section 14.3 of **Chapter 14** of the **ES [AS-079]**, the LOA demonstrates that the Proposed Development is substantially below the acceptable limits set out for Upward Flux Ratio (sky glow) and nuisance caused by lighting installation. The visible effects of obtrusive light within the Chilterns AONB would not be noticeable in the context of wider sky glow observed (during the time of survey). The LOA utilises and assesses 25 viewpoints identified within the LVIA, based on clear viewing towards the Main Application Site. Therefore, the modelled and quantified light levels reported in the LOA have been appropriately considered qualitatively using the methodology described in **Chapter 14** of the **ES [AS-079]** based on professional judgment of suitably qualified and experienced landscape architects and no further assessment is required as it is an appropriate methodology to assess night time effects from light sources in accordance with paragraph 6.12 of GLVIA3. (Ref 7) Para 4.27 refers to obtrusive light and '*reference should be made to appropriate guidance, such as that provided by the Institution of Lighting Professionals (ILP, 2011)'.* The assessment of impacts to cultural heritage assets as presented in paragraph 10.3.5 of **Chapter 10** of the **ES** [**AS-077**]] presents a holistic assessment of potential impacts, including those from lighting as reported in the LOA. With specific regard to Luton Hoo, the LOA included a specific viewpoint in order to fully understand the implications for the heritage asset. The LOA concluded that there would be a negligible change in lighting taking into consideration existing sky glow and existing light sources such as street lighting. This information was used to feed into the overall assessment of effects on the heritage significance of the parkland, which was assessed to be moderate adverse, which is significant.
Design			
53	Applicant and LBC to further discuss how design would be reviewed to ensure good design as required by paragraphs 4.29 to 4.35 of the Airport National Policy Statement and paragraph 126 of the NPPF, if it is not to be delivered through an independent design review panel.	On-going	The Applicant continues to engage with LBC on this issue and will report the latest position to the ExA at D7.
Heritage			
54	Questions on heritage to be asked as written questions as the Applicant's heritage expert was not available (see table below)	D7	Applicant to respond at D7.

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APPENDIX A: P19/DCO APPLICATION FLEETMIX COMPARISON TABLE

Appendix A P19/DCO Application Fleetmix Comparison Table

The table below reproduces the table from the P19 Environmental Statement Table 8B.1 based on the final reformatted version submitted to the P19 Inquiry. The two columns shown in red are the assumed fleet mix at 21.5 (Core Case) and 23 mppa (Faster Growth Case) in 2027 for the DCO. Figures in italics are business aviation or cargo flights. The percentage of new generation aircraft is stated for commercial passenger flights only.

	2023 18mppa		2023 Current Limit		2024 18mppa		2024 Current Limit		2025 19mppa		2025 Current Limit		2027 Core Case		27 Faster Growth Ca		2028 19mppa		2028 Current Limit		2031 19mppa	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
A300	*225*	*146*	*203*	*123*	*225*	*146*	*212*	*123*	*226*	*146*	*226*	*133*	*131*	*125*	*131*	*125*	*226*	*146*	*220*	*125*	*218*	*146*
A319ceo	2,560	360	2,304	304	1,760	289	1,654	245	2,010	347	2,010	316	-	-	-	-	49	n/a	48	n/a	-	-
A320ceo	7,440	1,296	6,696	1,092	6,807	1,290	6,398	1,093	6,542	1,292	6,542	1,178	6,000	1,400	8,290	1,720	1,888	438	1,839	376	-	-
A320 neo	4,473	742	4,025	626	5,914	819	5,559	694	6,203	829	6,203	756	11,200	2,010	10,310	1,840	14,088	2,040	13,722	1,752	16,100	2,354
A321ceo	4,415	499	3,974	421	4,019	451	3,778	382	3,661	303	3,661	276	180	-	540	-	-	-	-	-	-	-
A321 neo	3,225	793	2,903	669	3,616	842	3,399	713	3,733	926	3,733	845	7,350	920	7,740	940	5,638	1,210	5,492	1,039	5,699	1,150
A330	*11*	-	*10*	-	*11*	-	*11*	-	*11*	-	*11*	-	*8*	*26*	*8*	*26*	*11*	-	*11*	-	*11*	-
B737-Max	1,033	254	930	214	1,787	277	1,680	234	3,804	675	3,804	615	2,280	540	1,780	540	4,108	758	4,001	651	4,954	805
B737-400	*12*	*103*	*11*	*87*	*12*	*103*	*12*	*87*	*13*	*103*	*13*	*94*	-	*48*	-	*48*	*13*	*103*	*12*	*88*	-	*103*
B737-500	20	-	18	-	20	-	19	-	21	-	21	-					21	-	21	-	-	-
B737-700	36	-	32	-	37	-	35	-	39	-	39	-					39	-	38	-	-	-
B737-800/73H	3,588	551	3,229	465	2,835	529	2,665	448	824	132	824	121	2,800	550	3,730	570	541	49	527	42	-	-
B737-900	189	40	170	34	189	40	178	34	190	40	190	36	180	-	180	-	190	40	185	34	-	-
B757	*n/a*	*128*	*n/a*	*108*	*n/a*	*128*	*n/a*	*109*	*n/a*	*129*	*n/a*	*117*	*42*	*191*	*42*	*191*	*n/a*	*129*	*n/a*	*111*	-	*129*
B787-800/900	17	-	15	-	17	-	16	-	17	-	17	-					29	-	28	-	29	-
E135/145	340	-	306	-	353	-	332	-	366	-	366	-					366	-	357	-	366	-
E175/195	n/a	n/a	n/a	n/a	10	n/a	10	n/a	11	n/a	11	n/a					11	n/a	10	n/a	11	-
OTHER	*7,120*	*81*	*6,408*	*68*	*7,389*	*84*	*6,945*	*71*	*7,660*	*87*	*7,660*	*79*	*7,883*	*67*	*7,883*	*67*	*7,631*	*90*	*7,433*	*77*	*7,600*	*78*
Total	34,706	4,994	31,235	4,210	35,003	4,997	32,903	4,232	35,331	5,007	35,331	4,566	38,054	5,877	40,634	6,067	34,849	5,002	33,943	4,297	34,987	4,765
% New Gen (Pax fleet	32%	39%	32%	39%	41%	43%	41%	43%	50%	53%	50%	53%	69%	64%	61%	59%	88%	88%	88%	88%	99%	100%

Post hearing note: Mr Lambourne for LADACAN queried the figure of 38.9% for the proportion of new generation aircraft currently in use at London Luton Airport (as at October 2023) and cited a lower figure of c.31% at ISH8. The Applicant has discussed this discrepancy with Mr Lambourne and it is agreed that 31% refers to all aircraft movements whereas the Applicant was citing commercial passenger aircraft movements only.

APPENDIX B:WHO ENVIRONMENTAL NOISE GUIDELINES FOR THE EUROPEAN REGION: A SYSTEMATIC REVIEW ON ENVIRONMENTAL NOISE AND EFFECTS ON SLEEP

International Journal of
Environmental Research and Public Health

MDPI

Review

WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Effects on Sleep

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Received: 6 November 2017; Accepted: 2 March 2018; Published: 14 March 2018

Abstract: To evaluate the quality of available evidence on the effects of environmental noise exposure on sleep a systematic review was conducted. The databases PSYCINFO, PubMed, Science Direct, Scopus, Web of Science and the TNO Repository were searched for non-laboratory studies on the effects of environmental noise on sleep with measured or predicted noise levels and published in or after the year 2000. The quality of the evidence was assessed using GRADE criteria. Seventy four studies predominately conducted between 2000 and 2015 were included in the review. A meta-analysis of surveys linking road, rail, and aircraft noise exposure to self-reports of sleep disturbance was conducted. The odds ratio for the percent highly sleep disturbed for a 10 dB increase in L_{night} was significant for aircraft (1.94; 95% CI 1.61–2.3), road (2.13; 95% CI 1.82–2.48), and rail (3.06; 95% CI 2.38–3.93) noise when the question referred to noise, but non-significant for aircraft (1.17; 95% CI 0.54–2.53), road (1.09; 95% CI 0.94–1.27), and rail (1.27; 95% CI 0.89–1.81) noise when the question did not refer to noise. A pooled analysis of polysomnographic studies on the acute effects of transportation noise on sleep was also conducted and the unadjusted odds ratio for the probability of awakening for a 10 dBA increase in the indoor L_{max} was significant for aircraft (1.35; 95% CI 1.22–1.50), road (1.36; 95% CI 1.19–1.55), and rail (1.35; 95% CI 1.21–1.52) noise. Due to a limited number of studies and the use of different outcome measures, a narrative review only was conducted for motility, cardiac and blood pressure outcomes, and for children's sleep. The effect of wind turbine and hospital noise on sleep was also assessed. Based on the available evidence, transportation noise affects objectively measured sleep physiology and subjectively assessed sleep disturbance in adults. For other outcome measures and noise sources the examined evidence was conflicting or only emerging. According to GRADE criteria, the quality of the evidence was moderate for cortical awakenings and self-reported sleep disturbance (for questions that referred to noise) induced by traffic noise, low for motility measures of traffic noise induced sleep disturbance, and very low for all other noise sources and investigated sleep outcomes.

Keywords: sleep; transportation noise; wind turbine noise; hospital noise

1. Introduction

Sleep is a biological imperative and a very active process that serves several vital functions [1]. Undisturbed sleep of sufficient length is essential for daytime alertness and performance, quality of life, and health [2]. Noise has been shown to fragment sleep, reduce sleep continuity, and reduce total sleep time [3,4]. Numerous experimental studies have demonstrated that sleep restriction causes, among others, changes in glucose metabolism and appetite regulation, an attenuated immune response to vaccination, impaired memory consolidation, and dysfunction of blood vessels [5–10]. These are precursors for manifest diseases like obesity, diabetes, high blood pressure, and probably also dementia [11,12]. The epidemiologic evidence that chronically disturbed or curtailed sleep is associated with the negative health outcomes mentioned above is overwhelming [1,13]. For these reasons, noise-induced sleep disturbance is considered one of the most important non-auditory effects of environmental noise exposure [14].

Sleep and the effects of noise on sleep can be measured in multiple ways [15]. The gold standard for measuring sleep is polysomnography, which is the simultaneous measurement of (at least) brain electrical potentials (electroencephalogram, EEG), eye movements (electrooculogram, EOG), and muscle tone (electromyogram, EMG). The night is usually divided into 30-s epochs and a sleep stage (or awake) is assigned to each epoch based on typical patterns in the EEG, EOG, and EMG and according to standard criteria [16,17]. Rapid eye movement (or REM) sleep is differentiated from non-REM stages S1 through S4 (or N1 through N3 according to the newer AASM criteria [17]). Stages S3 and S4 (or N3) are also called deep or slow wave sleep (SWS). Continuous bouts of SWS and REM sleep are important for memory consolidation and sleep recuperation, while superficial sleep stage S1 and wake time do not relevantly contribute to sleep recuperation [18]. Polysomnography is currently the only methodology that provides detailed information on sleep stages, sleep structure, and shorter cortical arousals. However, it is somewhat invasive, and trained personnel are needed to attach and detach electrodes and to visually score sleep stages (with known inter-rater variability [19]). This restricts the sample size and generalizability of polysomnographic studies. Simpler methods with similar informative value compared to polysomnography are needed to increase generalizability of noise-effects studies [20].

Other less invasive but typically less sensitive methods include actigraphy and signaled awakenings. Actigraphy infers sleep or wake from wrist movements measured with a watch-like device that is usually worn for 24 h [21]. These devices have been introduced to the consumer market and have become more and more popular over the past years, with potential avenues for future noise-effects research. In studies using signaled awakenings, participants are asked to push a button whenever they wake up during the night, which requires both waking consciousness and the motivation of the subject to push the button, which explains the low sensitivity of this methodology. Finally, questionnaires may be used to ask about awakenings, sleep latency and other aspects of sleep quality. They can refer to the last night or to longer time periods. As humans are unconscious for most of the sleep period, subjective assessments of sleep may not agree with objective measurements, and misattributions are possible (e.g., a subject wakes up spontaneously, regains consciousness, and then perceives a noise event). Also, the subject may use his/her answer to make a political statement if the question explicitly asks about the effect of a noise source. Regardless of the limitations outlined above, self-assessments of sleep disturbance are nevertheless important endpoints for studies on the effects of noise on sleep, and they have been used successfully to describe exposure-response relationships and inform analyses on the burden of environmental noise on disease [14,22]. The different methods for measuring sleep are discussed in greater detail in Basner et al. [15].

The auditory system has a watchman function and constantly scans the environment for potential threats. Humans perceive, evaluate and react to environmental sounds even while asleep [23]. At the same sound pressure level, meaningful noise events are therefore more likely to cause arousals from sleep than less meaningful events. During the night, noise can often be described as intermittent (i.e., discrete noise events rather than a constant background noise level). In this case, the effects on sleep are primarily determined by the number and acoustical properties (e.g., maximum SPL, spectral composition) of single noise events (Figure 1). Noise may be accompanied by vibrations (e.g., rail noise), and the combination of noise and vibration induces higher degrees of sleep disturbance than noise alone [24]. Whether or not noise will disturb sleep also depends on situational (e.g., depth of sleep phase [25], background noise level [26]) and individual (e.g., noise sensitivity) moderators [23]. Repeated noise-induced arousals impair sleep quality and recuperation through changes in sleep structure including reduced sleep continuity [27], delayed sleep onset and early awakenings, less deep and REM sleep, and more time spent awake and in superficial sleep stages (Figure 1) [25,28]. Noise may also prevent a subject from falling asleep again after a spontaneous or noise-induced awakening. Deep and REM sleep have been shown to be important for sleep recuperation in general and memory consolidation specifically [10].

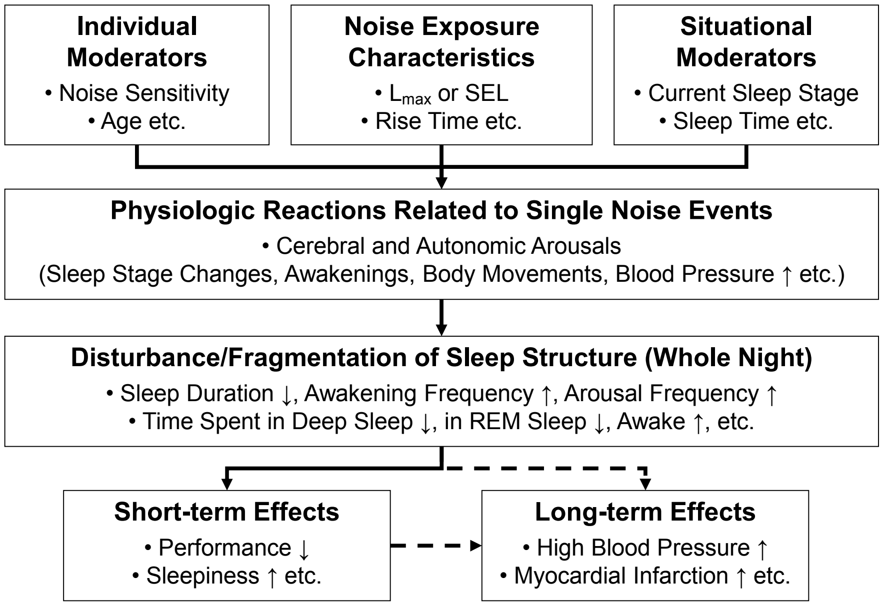

Figure 1. Effects of noise on sleep. It is hypothesized that health consequences will develop if sleep is relevantly disturbed by noise over long time periods (dashed lines; figure reproduced from Basner et al. [25]).

Non-acoustic factors can also affect sleep: external (e.g., high temperature and humidity) and internal (e.g., sleep disorders, nightmares) factors may induce arousals from sleep, complicating the unequivocal attribution of arousals from sleep to noise [29]. At the same time, classical indicators of fragmented sleep (e.g., awakenings, body movements) are part of the physiological sleep process and occur multiple times throughout the night in healthy sleepers and environments without external stressors, with no pathologic consequences. For example, a healthy adult briefly awakens ca. 20 times during an 8 h bed period (most of these awakenings are too short to be remembered the next morning) [30]. It is currently unclear how many additional noise-induced awakenings are acceptable and without consequences for sleep recuperation and health, especially given the large inter-individual differences in the susceptibility to noise. Although compensatory mechanisms have been observed [28], it is unclear at what point these mechanisms are exhausted or what biological cost they carry. In typical noise scenarios, noise-induced sleep-disturbance is usually less severe than, e.g., that observed in clinical sleep disorders like obstructive sleep apnea [31].

Short-term effects of noise-induced sleep disturbance include impaired mood, subjectively and objectively increased daytime sleepiness, and impaired cognitive performance [32,33]. It is hypothesized that noise-induced sleep disturbance contributes to the increased risk of cardiovascular disease if individuals are exposed to relevant noise levels over months and years (dashed lines in Figure 1). Recent epidemiologic studies indicate that nocturnal noise exposure may be more relevant for the genesis of long-term health outcomes like cardiovascular disease than daytime noise exposure, probably also due to the fact that people more consistently are at home during the night than during the day [34]. Given the many vital biological functions of sleep, and the fact that acutely curtailed or fragmented sleep has immediate consequences for next day alertness and performance, the effects of noise on sleep should not solely be judged based on long-term health consequences. Sleeping satisfies a basic need and is pleasurable if undisturbed and of sufficient length (very much like eating when hungry). Sufficient sleep increases, among others, alertness, mood, productivity, and creativity [2].

Therefore, sleep disturbance (induced by noise or other external or internal factors) needs to be minimized even without clearly established links to long-term health consequences.

One of the main goals of noise effects research is to derive exposure-response functions that can then be used for health impact assessments and ultimately to inform political decision making [3]. Numerous studies have associated several transportation noise sources (e.g., road, rail, and aircraft noise) with awakenings, briefer brain activations, and vegetative arousals (e.g., increases in heart rate and blood pressure) in both laboratory and field settings [25]. Unfortunately, sample sizes and response rates of the studies that are the basis for exposure-response functions were usually low, which restricts generalizability of the latter. These functions are usually sigmoidal (s-shaped) and show monotonically increasing reaction probabilities with increasing maximum sound pressure levels (SPL) or sound exposure levels (SEL). Maximum SPLs as low as 33 dBA induce physiological reactions during sleep, i.e., once the organism is able to differentiate a noise event from the background, physiologic reactions can be expected (albeit with a low probability at low noise levels) [35]. This reaction threshold should not be confused with limit values used in legislative and policy settings, which are usually considerably higher. As exposure-response functions are typically without a clearly discernible sudden increase in sleep disturbance at a specific noise level and because of individual variation in noise sensitivity, defining limit values is not a straightforward task. It usually involves expert judgement of the existing evidence (e.g., Night Noise Guidelines [36]), and political weighing of negative health consequences of noise and societal benefits of the noise source.

Equivalent noise levels are often used in surveys and epidemiologic studies as long-term average exposure metrics, and are therefore also often found in legislative and policy contexts. For example, the Night Noise Guidelines for Europe of the World Health Organization (WHO) define effects of nocturnal noise based on annual average outdoor L_{night} ranges [36]. The value of equivalent noise levels in describing the effects of noise on sleep is more limited, as different noise scenarios may calculate to the same equivalent noise level, but differ substantially in their sleep disturbing properties [25]. There is general agreement that the number and acoustical properties of single noise events better reflect the actual degree of nocturnal sleep disturbance in a single night [35]. It is thus questionable whether L_{night} can be used as the only indicator for predicting the effects of noise on sleep and the consequences of noise-induced sleep disturbance, or whether supplemental noise indicators are needed [25].

Subjects exposed to noise usually habituate. For example, the probability that noise causes physiologic reactions is in general higher during the first nights of a laboratory experiment compared to the last nights [28], and exposure-response relationships derived in the field (where subjects have often been exposed to the noise for many years) are usually much shallower than those derived in laboratory settings, which often include exposure to unfamiliar noise events in an unfamiliar environment [35,37]. Habituation is a reasonable mechanism that preserves energy resources. However, habituation is not complete, i.e., subjects continue to react to noise events even after several years of noise exposure. Unfortunately, little is known about individual differences in the ability to habituate to noise and potential predictors. Importantly, activations of the vegetative nervous system habituate to a much lesser degree to noise compared to cortical arousals. They provide biologic plausibility for the observed association between long-term noise exposure and cardiovascular disease [28,38,39]. It is also possible that exposed subjects become more sensitive to the effects of noise on sleep. This sensitization may be related to, e.g., individual changes (like aging, new incident disease), changes in noise exposure, or changes in media coverage. However, scientific knowledge about noise sensitization is currently very limited.

Sensitivity to nocturnal noise exposure varies considerably between individuals. Little is known about characteristics that predict someone's sensitivity to nocturnal noise-exposure. Men were found to be more sensitive to traffic noise than women [28], and specific features in the electric potentials generated by the brain (so-called sleep spindles) were associated with resiliance to noise-induced sleep disturbance [23]. The elderly, children, shift-workers, and patients with pre-existing (sleep) disorders are considered risk groups for noise-induced sleep disturbance [4]. Hospitals are often required to have additional sound insulation to reflect the increased sensitivity of the patient population.

In conclusion, undisturbed sleep is a prerequisite for high daytime performance, well-being and health. Environmental noise can disturb sleep and impair sleep recuperation. Reliable and up-to-date exposure-response relationships between environmental noise exposure and sleep disturbance are needed to inform political decision making and to help mitigate the effects of environmental noise on sleep. To provide updated recommendations since the last guidelines, we performed a systematic review of the literature on the effects of noise on sleep published in or after the year 2000. We performed a meta-analysis of surveys linking environmental noise exposure to self-reports of troubles falling asleep, awakening during the night, and sleep disturbance, and derived exposure-response relationships. We also performed a pooled analysis of studies on the acute effects of road, rail, and aircraft noise on sleep, and derived exposure-response functions between the maximum sound pressure level of individual noise events and the probability to wake up.

2. Methods

2.1. Mapping of Identified Reviews

A search for reviews on the effects of environmental noise on sleep was completed by WHO during spring 2014. The purpose was to determine if there were existing systematic reviews that could be used to provide evidence on noise and sleep outcome measures. In the literature search, sixteen reviews were identified. The quality of reviews was evaluated using the AMSTAR criteria [40]. Nine of the reviews were excluded as they did not have an a priori design, did not include a comprehensive literature review, or were on a topic irrelevant for this evidence review [41–49]. Of the seven remaining reviews, two examined the effects of noise on sleep in specific geographic regions only [50,51], one review only included studies in which there was a change in noise level [52] (a topic covered within the intervention evidence review), and 1 review only included studies that examined the relationship between sleep outcomes and noise sensitivity not the association with noise level [53]. The three remaining reviews were broader in content and examined the effects of aircraft [54], ambient [55], and wind turbine noise on sleep [56]. Data from individual studies were not pooled in any of the reviews; results from individual studies were presented qualitatively only. Therefore, it was determined that for all sleep outcome measures an updated search and review of individual studies would need to be conducted.

2.2. Search for Individual Studies

A search for individual studies was conducted by WHO which resulted in a total of 1159 hits. This search was not restricted by the year of publication. The titles and abstracts of these papers were reviewed by two independent reviewers and 51 were determined to be on relevant topics. The search terms included the study design (prospective, retrospective, cohort, longitudinal, cross-sectional, case control, ecological), type of noise source (environmental, community, traffic, railway, wind, aircraft, leisure, hospital) and outcome measure (insomnia, sleep, cortical awakening and arousal, autonomic arousal). After conducting this initial search, it was determined that several key papers in the field were not identified. Therefore, a second literature search was conducted using the same terms as provided by WHO, except terms that referred to study design were removed as they are not always applicable to studies on the effects of noise on sleep (the exact search term can be found in Section S6 of the supplement). The second literature search resulted in 10,029 hits and 216 additional papers were identified after reviewing titles and abstracts. The databases searched included PSYCINFO, PubMed, Science Direct, Scopus, Web of Science and the TNO Repository. A total of 69 additional papers which were mentioned in the identified literature reviews and in the meta-analysis by Miedema and Vos (2007) [22] were also included. Therefore, the literature search resulted in a total of 336 identified papers. The search also included gray literature, ICBEN and INCE conference proceedings were searched. The two literature searches were conducted in 2014. Additional searches were conducted on 30 July 2015 and 1 December 2015 to identify any additional studies while finalizing this review, two additional reports on transportation noise, one on hospital noise, and three on wind turbine noise were included based on these final searches.

2.3. Inclusion and Exclusion Criteria

Not all of the individual studies identified in the literature search were included in this evidence review. For all noise sources, studies conducted in the laboratory or those studies in which sounds were played back artificially were excluded due to low ecological validity. Studies conducted in the laboratory or studies that play back artificial sounds have typically found a higher probability of awakening to noise events than field studies [37,57,58]. Intervention studies (except for hospital noise) were excluded as they were covered in the intervention evidence reviews. Also, studies on sleep medication use were not covered in this review, as they initially were supposed to be covered in the mental health evidence review. However, the latter does not specifically cover sleep medication use. This is a limitation of this review, as sleep medication use can be an important indicator for noise-induced sleep disturbance. Sleep medication use is covered in the Night Noise Guidelines for Europe [36], and the reader is referred to those for a relatively recent review. In addition, for road, rail, and aircraft noise, only those studies published in the year 2000 or later were included, as this review is meant to be an update since the last guidelines. All studies on hospital noise were included though as this topic was not covered in detail in the previous guidelines. To be included in the review, studies must also have included measured or predicted noise levels for the participant's home; those that only included subjective evaluations of the noise or distance to the noise source were excluded. Studies that included noise levels not specific to the participant's home address were also excluded. Also studies had to have at least 2 different noise level categories examined in the study. In total 74 studies contributed to this review. Studies that did not meet the inclusion criteria and were excluded from the qualitative and quantitative analysis are listed in section S7 of the Supplement. A flow diagram of the selection and elimination of studies is shown in Figure 2.

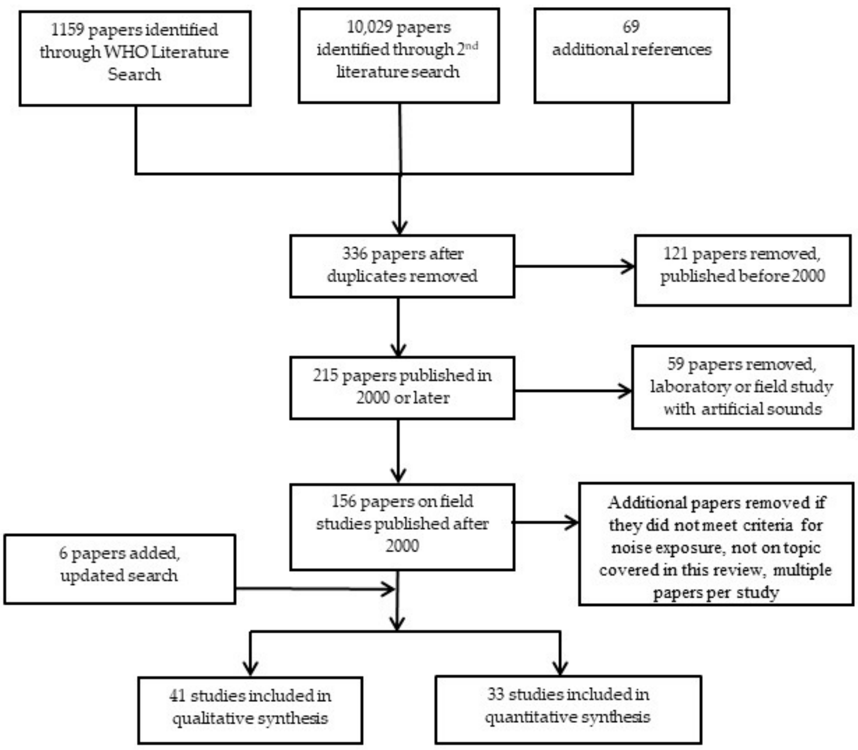

Figure 2. Flow of study selection.

2.4. Risk of Bias and Quality Assessment

Socio-economic status, age and gender were considered important confounders (i.e., variables associated both with the exposure and the outcome), but the use of these variables for adjustment was variable, so we did not exclude studies based on whether or not they adjusted for confounding by these variables.

The risk of bias in the studies reviewed is primarily a consequence of (a) the methodology used to measure sleep and noise-induced sleep disturbance and (b) the willingness of subjects to participate in a study on the effects of noise on sleep. Unfortunately, (a) and (b) are inversely related in such a way that less biased measurement techniques are associated with a higher selection bias and vice versa.

Information bias: Those studies that used polysomnography, or made continuous heart rate and blood pressure measurements during the sleep period were considered to have the lowest risk of information bias. Polysomnography, the simultaneous measurement of the electroencephalogram (EEG—brain activity), electrooculogram (EOG—eye movement), and electromyogram (EMG—skeletal muscle tone), is considered the gold standard for measuring sleep, and evaluating sleep fragmentation and sleep structure. However, electrodes cause some discomfort, may influence sleep (especially during the first measurement night), and thus introduce bias. Heart rate and blood pressure during the night will increase when an individual has brief autonomic or cortical arousals and therefore these measurements also provide a sensitive measure of sleep fragmentation [20].

The risk of information bias for studies that measured motility was considered moderate. Motility is measured typically using wrist worn devices (i.e., actigraphs). While awakenings or arousals during the night often occur together, individuals can be awake without moving which results in misclassification. Comparison studies between awakenings identified using actigraphy and polysomnography have found high sensitivity in identifying sleep epochs during the night but a low specificity (below 0.40) in identifying wake epochs [59].

Studies in which self-reported measures of sleep were used were considered to have a high risk of information bias. Subjects are not aware of themselves and their surroundings for most of the night, and relevant physiologic reactions are often not consciously perceived and remembered in the morning. Also, misattributions are possible (e.g., a subject wakes up spontaneously, regains consciousness, and then perceives a noise event). When studies specifically ask about how a particular noise source affects sleep, an individual’s response may (at least partially) reflect his or her attitude or feelings toward nighttime noise rather than disrupted sleep itself.

Information bias could occur not only due to sleep measurement methods, but also could arise from the methods used to quantify environmental noise. Due to variability in traffic across days, noise measurements should be made over a sufficient time period (minimally 1 week). For noise predictions, at a minimum data that is representative of the current traffic patterns should be used in the calculations for a study to have low risk of bias.

Selection bias: While studies using polysomnography for the measurement of sleep may have low information bias, they suffer from high selection bias. These studies often only include healthy individuals without sleep disorders. Due to the high methodological expense, sample sizes are typically low. Therefore the results may not be representative of the effects of noise on sleep in the general population. In addition, response rates for taking part in these studies are low as the instrumentation for measuring sleep requires trained personal to go to participant’s home each night and morning to apply and remove the electrodes, and the equipment that needs to be worn induces discomfort. Compared to studies using PSG, studies relying on self-reported sleep, in which participants are asked to fill out a questionnaire or complete an interview, have in general lower selection bias, higher response rates, and larger sample sizes. The results may therefore be more representative of the general population. However, this methodology also suffers from the highest information bias.

Publication bias: Publication bias refers to the fact that studies with positive findings are more often both submitted to and accepted by scientific journals. This likely biases the published studies to positive findings. It is, however, difficult to assess the consequences of publication bias.

3. Polysomnography Measured Cortical Awakenings for Road, Rail, and Aircraft Noise

As described in detail in Section 1, polysomnography is considered the gold standard for measuring sleep, its structure, and related events. Sleep structure varies systematically over the course of the night, with deep sleep (stages 3 or 4, or N3 according to the new classification) dominating the first half of the night and REM sleep and superficial sleep stages 1 and 2 (or N1 and N2) dominating the second half of the night. Field studies (including the four studies discussed in detail below [35,60–62]) typically allow subjects to adhere to their normal bed times. Sleep duration thus varies systematically both between subjects but also within subjects (if a subject is measured for multiple nights). This within- and between-subject variability in sleep duration complicates the assessment of the effects of noise on sleep duration and whole night sleep parameters, and introduces substantial non-noise variance to the data. Even sleep architecture (i.e., the distribution of sleep stages) will be affected by fluctuations in sleep period duration (regardless of whether sleep stages are expressed in minutes or % of sleep period time), as sleep stages are not evenly distributed over the course of the night. For these reasons, we concentrated our analysis on the effects of traffic noise on sleep on the reaction of the sleeper to single noise events. Spontaneous and noise-induced awakenings also increase with increasing sleep period time, but it is relatively easy to account for the latter in single event analyses. Furthermore, relationships between whole-night noise exposure descriptors (i.e., L_{night}) and single event metric outcomes (i.e., awakenings) have been previously described, and the reader is referred to these [25].

Four studies were identified on study selection for which the effects of road, rail, or aircraft noise on polysomnographically measured sleep was evaluated. Two studies identified in the literature review but not included in the re-analysis include one road traffic and rail noise study and one aircraft noise study. Aasvang et al. [61] conducted a field study examining the effect of railway and road traffic noise on sleep in Oslo, Norway. Twenty of the subjects were exposed to railway noise and twenty to road traffic noise. The subjects participated for two consecutive nights. Several sleep variables were examined in relation to the maximum noise level inside the bedroom for the entire night due to road traffic or rail noise. Wake after sleep onset (WASO) was found to increase with the maximum noise level of train noise with a 30 min increase in WASO found for those subjects exposed to noise levels above 50 dBA compared to those exposed to levels less than 50 dBA. Also a decrease in REM sleep with noise level was found with rail noise, however no significant changes in any sleep parameter was found for road traffic noise. The data from the study by Aasvang et al. [61] was not included in the re-analysis because single transportation noise events and associated awakenings had not been scored. Flindell et al. [62] conducted a study on the effects of aircraft noise around Manchester airport. Eighteen subjects took part for 5 consecutive nights. All subjects were between the ages of 30 to 40 years old. Noise levels were recorded within the bedroom. There was no significant change in sleep between a high noise and a low noise area, but the indoor noise exposure in both areas was similar. The study found increases in the number of awakenings, total durations of stage 1 sleep, number of REM sleep periods and changes in the frequency content of the EEG associated with higher numbers of ANEs occurring during the sleep period. The data from the Flindell et al. [62] study was not available for inclusion in the re-analysis.

Single event based analysis was completed in two studies conducted by the German Aerospace Center (DLR), both of which used similar methodology and were included in the re-analysis. The STRAIN study was conducted to investigate the effect of aircraft noise on sleep [35]. The study was conducted between September 2001 and November 2002 and included 64 residents between the ages of 18 to 61 years (average age 38 years, 55% female) who lived around Cologne-Bonn Airport. The DEUFRAKO study was conducted to investigate the effect of rail noise on polysomnographically measured sleep [60]. The study was conducted between February 2008 and July 2009 and included 33 individuals between the ages of 22 and 68 years (average age 36 years, 67% female) who lived near Cologne and Bonn close to railway lines. In both studies, subjects participated for nine consecutive nights and indoor noise levels were recorded in the bedroom. Physiological reactions to road traffic noise were also measured. The raw data for these two datasets were obtained from DLR and used to derive exposure-response relationships for the probability of a sleep stage change to wake or S1; the STRAIN dataset was used for aircraft noise, the DEUFRAKO dataset was used for train noise, and the STRAIN and DEUFRAKO data were combined for road traffic noise.

3.1. Event-Related Analysis

For both studies, sleep stages were scored according to the standard criteria of Rechtschaffen and Kales using 30-s epochs [16]. Epochs scored as Movement Time were re-classified as wake. Individuals who visually scored the polysomnography data were blinded to the occurrence of noise events. For the STRAIN study, data from 61 of the 64 participants contributed to the analysis, two were excluded due to constant snoring and one was excluded due to an intrinsic sleep disorder.

Road, rail, and aircraft events were identified by listening to indoor sound recordings and the start and end of each noise event was scored. For each noise event, the first sleep stage affected by a noise event (first noise epoch) was defined as the first epoch that contained more than 15 s of the event [35]. If the subject was asleep in the epoch prior to the first noise epoch (Stages 2, 3, 4, or REM sleep) then the next three epochs (90 s) were screened for a transition to wake or Stage S1.

During a road, rail, or aircraft event, additional outdoor or indoor noises can occur. In this analysis a noise event was considered 'undisturbed' if the following criteria were met: (1) only events from the same noise source could occur one minute before (e.g., the end of a prior noise event) and 1.5 min after the start of the event and (2) sounds made by the subject such as turning over in bed were allowed before and during the noise event of interest as they could be reactions to the noise. Events defined as 'disturbed' consisted of those in which any other noise event occurred 60 s prior or up to 1.5 min after the start of the first noise epoch.

3.2. Statistical Analysis

For the analysis, each noise event was annotated with its maximum sound pressure level ($L_{AS,max}$), the age and gender of the exposed subject, the day of the week (weekday/weekend), and time from sleep onset. The primary outcome is binary and reflects an awakening or sleep stage change to stage 1 (1) or no such change in sleep structure (0). Random subject effect logistic regression models with the maximum indoor noise level ($L_{AS,max}$) as the only predictor were performed with the NLMIXED procedure in SAS (version 9.3, SAS institute, Cary, NC, USA), based on the event-related data. The non-liner models were calculated to reflect the clustered nature of the data (i.e., that each subject was exposed to multiple noise events). Both unadjusted models and models adjusted for age, gender, weekday, and time from sleep onset were calculated. Point estimates and 95% confidence intervals were generated with estimate statements in Proc NLMIXED. Unadjusted models were used to derive the exposure-response relationships. While additional factors such as prior sleep stage, time of night, duration of the event, age, gender have been found to be important effect moderators [35,60], assumptions have to be made for the values of these parameters when deriving exposure-response relationships between noise level and probability of awakening. Therefore, only the noise level of the event was included when deriving these models.

430 subject nights of data from the STRAIN study and 277 subject nights from the DEUFRAKO study contributed to the analysis. Exposure-response relationships for all transportation modes, for only undisturbed events and both disturbed and undisturbed events were calculated and the results are shown in Figure 3. This analysis was completed to examine the potential bias in the exposure-response curves when including or excluding specific noise events. The exposure-response functions are for the probability of a transition to wake and Stage 1 because in the DEUFRAKO study more Stage 1 sleep was scored than in the STRAIN dataset (23.3 min versus 16.6 min), which may be due to inter-rater variability in scoring.

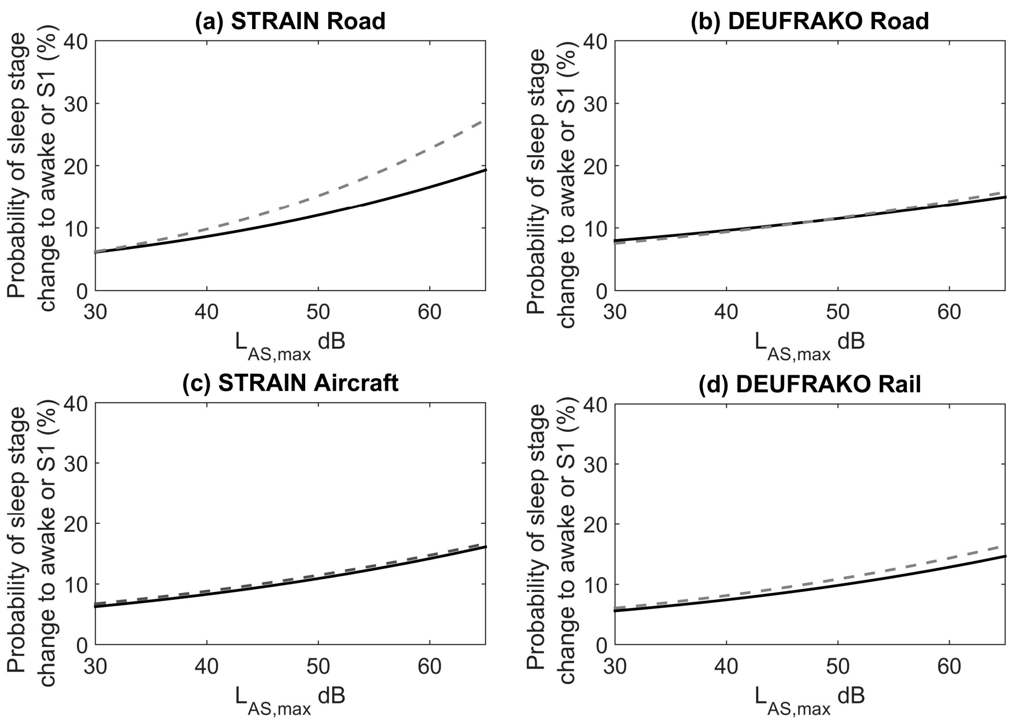

Figure 3. Probability of a sleep stage change to awake or S1 in a 90 second time window following noise event onset depending on the maximum indoor sound pressure level ($L_{AS,max}$) for (**a**) STRAIN road traffic (*N* = 61 subjects); (**b**) DEUFRAKO road traffic (*N* = 33); (**c**) STRAIN aircraft (*N* = 61); and (**d**) DEUFRAKO rail noise events (*N* = 33). Undisturbed events only (black), all events including disturbed and undisturbed events (gray dotted line).

When all events were included in the analysis there was a higher probability of transitions to wake and S1 for road traffic noise in the STRAIN study compared to the probability for transitions for undisturbed noise events. This may be due to simultaneous aircraft noise events that increase awakening probability. However, this was not found for the DEUFRAKO study. For the other noise sources there were only small non-significant changes in the exposure-response relationships when including disturbed noise events. Due to the difference for road traffic noise, however, for the remaining analysis only the undisturbed events were used. The number of noise events contributing to the analysis was 10,546 aircraft events, 7631 train events (including both passenger and freight trains), and 7101 road traffic events in the STRAIN study and 4407 events in the DEUFRAKO study. The road traffic events consisted primarily of single car or truck passings, 843 events consisted of multiple vehicles.

The three exposure-response curves for the undisturbed events are shown in Figure 4 for the slow weighted maximum noise level. The road noise data from the STRAIN and DEUFRAKO study were combined as estimates did not differ significantly between studies (OR per 10 dBA 1.45; 95% CI 1.22–1.73 for STRAIN and OR per 10 dBA 1.22; 95% CI 0.98–1.51 for DEUFRAKO, $p = 0.09$). The data for both passenger and freight trains in the DEUFRAKO study were combined as well (OR per 10 dBA 1.40; 95% CI 1.22–1.61 for freight trains and OR per 10 dBA 1.21; 95% CI 0.98–1.50 for passenger trains, $p = 0.31$). While the slow A-weighting is typically used for aircraft noise metrics, the fast weighting is often used for road and rail noise due to the faster temporal profile of the sounds. While not available for the STRAIN study, $L_{AF,max}$ levels were available for the DEUFRAKO study. The mean absolute difference between $L_{AF,max}$ and $L_{AS,max}$ levels was 0.86 dB (2.5–97.5% Range: 0–3.5 dBA) for road traffic, and 0.72 dB (2.5–97.5% Range: 0.0–4.0 dBA) for rail traffic. Overall the average difference in levels was less than 1 dBA and therefore all results are presented using $L_{AS,max}$ levels.

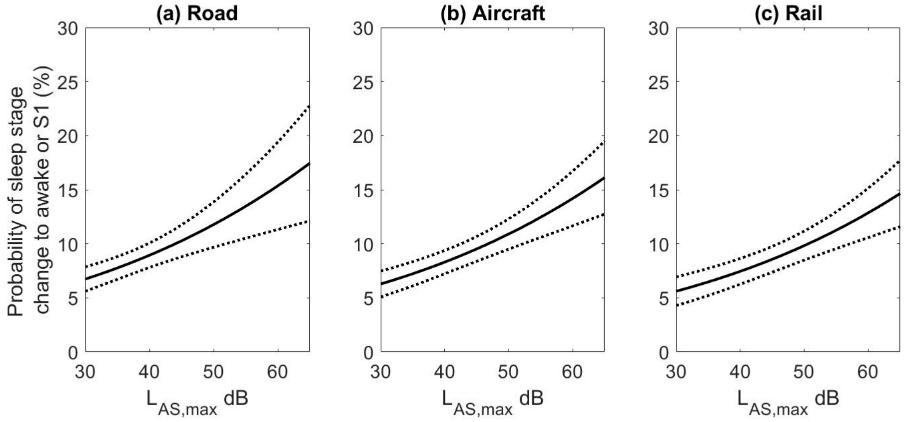

Figure 4. Probability of a sleep stage change to awake or S1 in a 90 s time window following noise event onset depending on the maximum indoor sound pressure level ($L_{AS,max}$) for (**a**) road (STRAIN and DEUFRAKO, *N* = 94 subjects); (**b**) aircraft (STRAIN, *N* = 61); and (**c**) rail noise (DEUFRAKO, *N* = 33). 95% confidence intervals (dashed lines). Results are for the unadjusted model.

The distribution of indoor noise levels and the timing of events relative to sleep onset for each noise source are shown in Figure 5. The unadjusted odds ratio for sleep stage transitions to wake or Stage 1 for a 10 dBA increase in the slow weighted indoor maximum noise level ($L_{AS,max}$) for all three transportation modes was calculated and the results are shown in Table 1. All odds ratios were statistically significant and differed only marginally between traffic modes. Odds ratios adjusted for age and gender, and odds ratios adjusted for age, gender, day of the week (weekend or weekday), and time from sleep onset were also calculated. Adjusting only marginally reduced the odds ratios, and all estimates were still significantly different from 1. Data for additional confounding variables were not available.

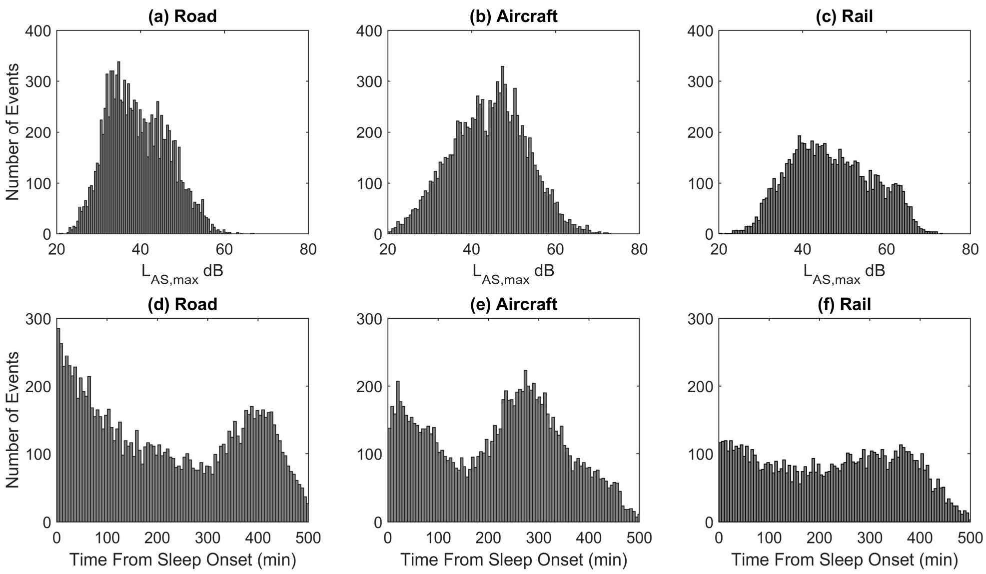

Figure 5. Distribution of indoor noise levels and the time of events relative to sleep onset for (**a**,**d**) road; (**b**,**e**) aircraft; and (**c**,**f**) rail events (all undisturbed noise events from the STRAIN and DEUFRAKO studies used for analysis).

Table 1. Odds Ratios and 95% confidence intervals for sleep stage transitions to awake or Stage 1 for road, rail, and aircraft noise for a 10 dBA increase in the indoor maximum noise level ($L_{AS,max}$). Number of subjects contributing to the analysis: Road = 94, Aircraft = 61, Rail = 33.

Odds Ratio per 10 dBA ($L_{AS,max}$)	Road (STRAIN and DEUFRAKO)	Aircraft (STRAIN)	Rail (DEUFRAKO)	Combined Estimate (Based on Road, Rail, and Aircraft)
Unadjusted	1.36 (1.19–1.55)	1.35 (1.22–1.50)	1.35 (1.21–1.52)	1.35 (1.25–1.45)
Adjusted for Age and Gender	1.36 (1.19–1.55)	1.35 (1.21–1.50)	1.34 (1.19–1.50)	1.28 (1.21–1.36)
Adjusted for Age, Gender, Day of the Week, and Time From Sleep Onset	1.32 (1.15–1.50)	1.32 (1.19–1.47)	1.34 (1.19–1.51)	1.29 (1.21–1.36)

Individuals will not only awaken during the night due to noise events but also spontaneously. It is because of these spontaneous reactions that in Figure 4, even for low noise levels the probability of sleep stage transitions to wake or S1 is greater than 5.0%. The probability of spontaneously awakening during the night was calculated separately for all three transportation sources using virtual events [57]. As each subject was investigated for several nights, the other study nights could be used to determine spontaneous awakening probability. For example, if a noise event occurred in study night #2 two hours after sleep onset, study nights #3–#9 were screened for spontaneous awakenings at the same time from sleep onset as the noise event if this time interval was determined to be free from transportation noise (night #1 was always discarded from the analysis due to a possible first-night effect [63]). The spontaneous awakening rates that were calculated were 6.1% for rail, 7.7% for aircraft, and 8.2% for road noise (all for 90-s intervals relative to onset of the virtual noise event). Three different rates of spontaneous awakening probability were calculated as the value is dependent on the time noise events occurred (as shown in Figure 5d–f the distribution of events during the night varied by noise source). In addition, different spontaneous rates were calculated because for each transportation mode the results are based on data from different subjects.

The spontaneous awakening probabilities were subtracted from the exposure-response curves, by including the value in the logistic regression equation when deriving the point estimates, to obtain the probability of having an additional awakening attributable to the noise event. Second order polynomials were fit to obtain exposure-response relationships. The exposure-response relationships obtained are shown in Figure 6.

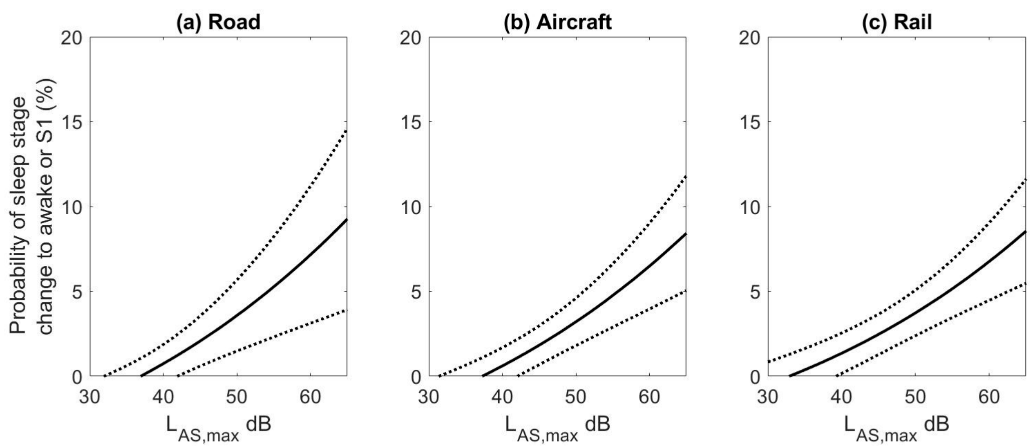

Figure 6. Probability of additional sleep stage changes to awake or S1 in a 90 s time window following noise event onset depending on the maximum indoor sound pressure level ($L_{AS,max}$) for (**a**) road (STRAIN and DEUFRAKO, N = 94 subjects); (**b**) aircraft (STRAIN, N = 61); and (**c**) rail noise (DEUFRAKO, N = 33). 95% confidence intervals (dashed lines). Results are for the three unadjusted models.

The equations for the probability of additional awakenings due to road, rail, and aircraft noise are:

$$\text{Road: Prob. of Wake or S1} = -3.3188 - 0.0478 * L_{AS,max} + 0.0037 * (L_{AS,max})^2 \quad (1)$$

$$\text{Aircraft: Prob. of Wake or S1} = -3.0918 - 0.0449 * L_{AS,max} + 0.0034 * (L_{AS,max})^2 \quad (2)$$

$$\text{Rail: Prob. of Wake or S1} = -1.7768 - 0.0529 * L_{AS,max} + 0.0033 * (L_{AS,max})^2 \quad (3)$$

3.3. Conclusions

In the re-analysis conducted, for all transportation modes a significant positive association was found between indoor maximum noise levels of single events and the probability of sleep stage transitions to wake or Stage 1. The noise levels at which the probability of an additional awakening was nonzero varied between transportation modes but was between 33–38 dBA, which is consistent with previous findings [35,64]. While for road traffic noise the odds ratio for awakenings was greater in the STRAIN study than in the DEUFRAKO study, no significant differences were found between the three transportation modes. This finding is in contradiction to the results of a laboratory study conducted by Basner et al. [28] in which road and rail traffic noise resulted in a greater probability of awakening than aircraft noise for events of the same noise level. Also these results are in contradiction to those of Aasvang et al. [61] who found that train noise had a greater effect on sleep than road traffic noise. However, the DEUFRAKO and STRAIN studies were not designed to specifically examine the effect of road traffic noise on sleep. A difference was also not found in awakening probability between train and aircraft noise. However, this comparison was conducted across studies. While polysomnography is a sensitive and objective measure of sleep, sleep stage scoring is performed visually and there can be both high intra- and inter-rater variability in the scoring [65]. Therefore, further studies are still needed in order to determine whether in the field setting the three types of transportation modes have a different effect on awakening probability.

In terms of the applicability of these results to the general population, all four of the studies identified in the review suffer from selection bias. Subjects in these studies were physically healthy and free of intrinsic sleep disorders. The effect of transportation noise on sleep in those with preexisting medical conditions is unknown; the results presented may underestimate the effect of noise on sleep in the general population. We were able to adjust odds ratios for the confounders age and gender, time from sleep onset, and day of the week but did not have access to a more comprehensive set of confounders. The exposure-response functions are based on unadjusted models that contained the maximum sound pressure level as the only predictor. Although the number of noise events that contributed to the exposure-response relationships was large, the latter are nevertheless based on data from a total of $N = 94$ subjects only and these subjects lived in geographically circumscribed regions in Germany. Thus, although the best data set currently available, it is unclear how the exposure-response relationships translate to other populations and regions. More studies with a higher degree in diversity of populations and regions are needed to inform future exposure-response functions.

Finally, it is unclear how the results from single event analyses translate to changes in sleep structure across the whole night, as time in bed is rarely fixed in field studies on the effects of noise on sleep and sleep stages are not evenly distributed across the night (see Section 3 for a discussion). Some research has shown that the body engages in compensatory mechanisms to keep the level of sleep fragmentation low [28]. However, noise-induced awakenings may come at a greater biological cost for recuperation than spontaneous awakenings that are part of the physiologic sleep process [29]. The two studies that did provide whole night sleep estimates also allowed variable individual bed times [61,62]. The limited evidence derived from these two studies does, however, support the notion that nocturnal traffic noise exposure contributes to sleep disturbance on the whole night level.

4. Self-Reported Sleep Outcomes for Road, Rail, and Aircraft Noise

After reviewing individual studies in which the effect of road, rail, or aircraft noise on self-reported sleep outcomes was measured, the decision was made to focus on the 3 most common outcomes, the definitions of which are:

- Awakenings from sleep, which refers to the period after sleep onset and before the final awakening. They are defined as events where a subject wakes up from sleep, regains consciousness, and recalls the awakening in the next morning.
- The process of falling asleep, which is defined as the transition from wakefulness into sleep.
- Sleep disturbance refers to internal/external interference with sleep onset or sleep continuity (sleep maintenance).

Results from surveys that contained general questions about sleep and surveys that included questions specifically on how noise affects sleep were included in the review. The results for self-reported sleep disturbance were not reported in the literature in a consistent manner; therefore in order to conduct a meta-analysis, the authors of the individual papers reviewed were contacted in order to obtain the number of participants who reported each response alternative for 5 dB noise categories. This information was obtained for 30 studies, which were used to derive exposure-response relationships for the percent highly sleep disturbed for the different sleep outcome measures. We were unable to obtain data from five studies. Data for confounding variables was not obtained for any of the studies. The number of participants in these studies and sleep questions used are listed in Tables 2–4.

4.1. Statistical Analysis

For the meta-analysis, the noise metric used was the average outdoor A-weighted noise level (L_{night}). All studies used this metric (although relative to different time periods), except for Bodin et al. (2015) who reported the average 24 h noise level ($L_{Aeq,24hr}$) [66]. The $L_{Aeq,24hr}$ was converted to L_{night} using linear equations between the two metrics that were derived based on the Swiss transportation noise map (sonBase). The equations used for road traffic and railway noise are:

$$\text{Road Traffic: } L_{night} = L_{Aeq,24h} - 6.0 \text{ dB} \quad (4)$$

$$\text{Railway: } L_{night} = L_{Aeq,24h} - 0.9 \text{ dB} \quad (5)$$

For most studies the noise metric was predicted or measured at the most exposed façade of the dwelling, not the bedroom. The L_{night} levels assigned for all studies were the midpoint of the 5 dB categories. For open-ended noise exposure categories (e.g., <50 or >50) the noise level assigned was 2.5 dB above or below the category, for example for <50 dB the assigned value would be 47.5 dB.

The approach used in this meta-analysis is not the same as the approach used by Miedema and Vos (2007) [22], who previously developed exposure-response models relating the percent highly sleep disturbed for road, rail, and aircraft noise based on survey response data. In their analysis, the survey response data used was available at the individual response level. The response scales for the questions on sleep disturbance varied between the studies used in their analysis. In order to derive a combined model, they translated the response categories for each question to a scale of 0 to 100 by dividing 100 by the number of response choices and multiplying by the rank of the response choice. They modeled a cumulative distribution function based on the assigned scores and then calculated the percent of the population that was estimated to have a score of 72% or higher, which was the cutoff point they defined as highly sleep disturbed, for different L_{night} levels.

For this analysis, data was not obtained at the individual level, results were not always obtained for all response categories, and questions were included in which the frequency or the severity of sleep disturbance was reported. Therefore instead of modeling sleep disturbance as a continuous function, the probability of being highly sleep disturbed was modeled. A binary variable was created for highly sleep disturbed. Following previous conventions used for the ICBEN annoyance scale, for questions that used a 5 point or 11 point scale, and referred to the severity of sleep disturbance the top two and top three categories, respectively, were defined as highly sleep disturbed. For the few questions that referred to the frequency of symptoms, such as Halonen et al. (2010) [67], response alternatives for symptoms occurring three times or more per week were considered highly sleep disturbed. This criterion was used, as having difficulty sleeping at least three times per week for at least one month is considered a diagnostic criterion of insomnia [68]. For other response scales, the response alternatives that were considered highly sleep disturbed are highlighted in the tables.

Table 2. Studies on aircraft noise and self-reported sleep disturbance (* general health survey, + noise survey). Studies modeled the noise levels except where indicated. Response alternatives contributing to the calculation of the percent Highly Sleep Disturbed are in bold.

Study	*N*	Country	Sleep Disturbance Questions	Noise Metric (Range for Obtained Data)
Falling Asleep (Total *N* = 6368)				
+ Nguyen et al. (2015) [69]	1095	Hanoi, Vietnam	In daily life, when an airplane passes by, at what degree are you disturbed in the following cases: When it makes it difficult for you to fall asleep? Not at all, Slightly, Moderately, **Very, Extremely**	L_{night}, 22:00–6:00, measured (1 week) (37.5–57.5)
+ Yano et al. (2015) [70]	780	Hanoi, Vietnam		L_{night}, 22:00–6:00, measured (1 week) (37.5–57.5)
+ Nguyen et al. (2012) [71]	512	Da Nang City, Vietnam		L_{night}, 22:00–6:00, measured (1 week) (37.5–52.5)
+ Nguyen et al. (2010) [72] Nguyen et al. (2011) [73]	805	Hanoi, Vietnam		L_{night}, 22:00–6:00, measured (1 week) (37.5–52.5)
+ Nguyen et al. (2009) [74]	868	Ho Chi Minh City, Vietnam		L_{night}, 22:00–6:00, measured (1 week) (42.5–62.5)
+ Schreckenberg et al. (2009) [75]	2308	Germany	How much has aircraft noise in the last 12 months disturbed falling asleep? Not at all, Slightly, Moderately, **Very, Extremely**.	L_{night}, 22:00–6:00 (37.5–57.5)
Awakenings (Total *N* = 4054)				
+ Nguyen et al. (2015) [69]	1093	Hanoi, Vietnam	In daily life, when an airplane passes by, to what degree are you disturbed in the following cases: When you are awakened in your sleep? Not at all, Slightly, Moderately, **Very, Extremely**.	L_{night}, 22:00–6:00, measured (1 week) (37.5–57.5)
+ Yano et al. (2015) [70]	776	Hanoi, Vietnam		L_{night}, 22:00–6:00, measured (1 week) (37.5–57.5)
+ Nguyen et al. (2012) [71]	511	Da Nang City, Vietnam		L_{night}, 22:00–6:00, measured (1 week) (37.5–52.5)
+ Nguyen et al. (2010) [72] Nguyen et al. (2011) [73]	804	Hanoi, Vietnam		L_{night}, 22:00–6:00, measured (1 week) (37.5–52.5)
+ Nguyen et al. (2009) [74]	870	Ho Chi Minh City, Vietnam		L_{night}, 22:00–6:00, measured (1 week) (42.5–62.5)
Sleep Disturbance (Total *N* = 2309)				
+ Schreckenberg et al. (2009) [75]	2309	Germany	How much has aircraft noise in the last 12 months disturbed sleeping during the night? Not at all, Slightly, Moderately, **Very, Extremely**.	L_{night}, 22:00–6:00 (37.5–57.5)
Falling Asleep-Noise source not specified in sleep questions (Total *N* = 2978)				
+ Brink et al. (2005) [76] 2001 Study	1528	Switzerland	How often do you have the following symptoms: Problems falling asleep? Never, Rarely, Sometimes, Often, **Very Often, Always**	L_{night}, 22:00–6:00 (27.5–62.5)
+ Brink et al. (2005) [76] 2003 Study	1450			L_{night}, 22:00–6:00 (27.5–62.5)

Table 2. *Cont.*

Study	*N*	Country	Sleep Disturbance Questions	Noise Metric (Range for Obtained Data)
Awakenings-Noise source not specified in sleep questions (Total *N* = 2978)				
+ Brink et al. (2005) [76] 2001 Study	1528	Switzerland	How often do you have the following symptoms: Problems with sleeping through? Never, Rarely, Sometimes, Often, **Very Often, Always**	L_{night}, 22:00–6:00 (27.5–62.5)
+ Brink et al. (2005) [76] 2003 Study	1450			L_{night}, 22:00–6:00 (27.5–62.5)
Sleep Disturbance-Noise source not specified in sleep questions (Total *N* = 195)				
* Brink (2011) [77]	195	Switzerland	During the last 4 weeks, have you suffered from any of the following disorders or health problems? Difficulty in sleeping or insomnia? Not at all, Somewhat, **Very Much**.	L_{night}, 22:00–6:00 (32.5–52.5)
				L_{night}, 22:00–6:00 (32.5–52.5)

Table 3. Studies on road noise and self-reported sleep disturbance (* general health survey, + noise survey). Studies modeled the noise levels except where indicated. Response alternatives contributing to calculation of the percent Highly Sleep Disturbed are in bold.

Study	*N*	Country	Sleep Disturbance Questions	Noise Metric (Range for Obtained Data)
Falling Asleep (Total *N* = 10,212)				
+ Bodin et al. (2015) [66]	2444	Sweden	Do you experience any of the following because of road traffic noise? Difficulties falling asleep. Never, Sometimes, **Often**.	L_{Aeq}, 24 h (37.5–62.5)
+ Sato et al. (2002) [78]	1302	Gothenburg, Sweden	Does the road traffic noise cause the following conditions? Difficulty to fall asleep? No, Little Disturbed, Rather Disturbed, **Very Disturbed**.	L_{night}, 22:00–7:00, measured (1 night) (42.5–72.5)
	814	Kumamoto, Japan		L_{night}, 22:00–7:00, measured (1 night) (47.5–77.5)
	779	Sapporo, Japan		L_{night}, 22:00–7:00, measured (1 night) (52.5–67.5)
+ Phan et al. (2010) [79] Shimoyama et al. (2014) [80]	1471	Hanoi, Vietnam	How much are you disturbed in falling asleep by road traffic? Not at all, Slightly, Moderately, **Very, Extremely**.	L_{night}, 22:00–6:00, measured (1 night) (62.5–77.5)
	1458	Ho Chi Minh City, Vietnam		L_{night}, 22:00–6:00, measured (1 night) (67.5–77.5)
	481	Da Nang, Vietnam		L_{night}, 22:00–6:00, measured (1 night) (57.5–67.5)
	682	Hue, Vietnam		L_{night}, 22:00–6:00, measured (1 night) (52.5–72.5)
	781	Thai Nguyen, Vietnam		L_{night}, 22:00–6:00, measured (1 night) (52.5–67.5)

Table 3. *Cont.*

Study	*N*	Country	Sleep Disturbance Questions	Noise Metric (Range for Obtained Data)
Awakenings (Total *N* = 10177)				
+ Bodin et al. (2015) [66]	2438	Sweden	Do you experience any of the following because of road traffic noise? You wake up? Never, Sometimes, **Often**.	L_{Aeq}, 24 h (37.5–62.5)
+ Sato et al. (2002) [78]	1291	Gothenburg, Sweden	Does the road traffic noise cause the following conditions? Awakening? No, Little Disturbed, Rather Disturbed, **Very Disturbed**.	L_{night}, 22:00–7:00, measured (1 night) (42.5–72.5)
	819	Kumamoto, Japan		L_{night}, 22:00–7:00, measured (1 night) (47.5–77.5)
	779	Sapporo, Japan		L_{night}, 22:00–7:00, measured (1 night) (52.5–67.5)
+ Phan et al. (2010) [79] Shimoyama et al. (2014) [80]	1454	Hanoi, Vietnam	How much are you disturbed by awakening during nighttime by road traffic? Not at all, Slightly, Moderately, **Very, Extremely**.	L_{night}, 22:00–6:00, measured (1 night) (62.5–77.5)
	1460	Ho Chi Minh City, Vietnam		L_{night}, 22:00–6:00, measured (1 night) (67.5–77.5)
	479	Da Nang, Vietnam		L_{night}, 22:00–6:00, measured (1 night) (57.5–67.5)
	680	Hue, Vietnam		L_{night}, 22:00–6:00, measured (1 night) (52.5–72.5)
	777	Thai Nguyen, Vietnam		L_{night}, 22:00–6:00, measured (1 night) (52.5–67.5)
Sleep Disturbance (Total *N* = 9901)				
+ Brown et al. (2015) [81]	8841	Hong Kong	How much is your sleep disturbed by road traffic noise? 11 point scale used from 0 (not disturbed at all) to 10 (extremely disturbed) **(8, 9, 10 HSD)**	L_{night} (42.5–67.5)
+ Hong et al. (2010) [82]	550	Korea	How much have you been disturbed in your sleep by road traffic noise at night when you are sleeping in your house over the last 12 months? 11 point scale used from 0 (not disturbed at all) to 10 (extremely disturbed) **(8, 9, 10 HSD)**	L_{night}, 22:00–7:00 (50.0–73.0)
+ Ristovska et al. (2009) [83]	510	Macedonia	Do you think that your sleep was disturbed due to night-time noise or noise events during the night in the last twelve months and more? Not at all, Very little, Moderate, **High, Very High**.	L_{night}, 23:00–7:00, measured (2 nights) (42.5–62.5)
Falling Asleep–Noise source not specified in sleep questions (*N* = 10,545)				
+ Bodin et al. (2015) [66]	2520	Sweden	Do you have problems falling asleep? Rarely/never, A few times per month, A few times a week, **Almost every day**	L_{Aeq}, 24 h (37.5–62.5)
* Halonen et al. (2012) [67]	6793	Finland	How many times during the past 4 weeks have you had the following symptoms? Difficulty falling asleep? Never, 1 per month, 1 per week, **2–4 per week, 5–6 per week, Nearly every night**.	L_{night}, 22:00–7:00 (42.5–57.5)
* Frei et al. (2014) [84]	1232	Switzerland	How often does it happen, that you cannot fall asleep well? Never, Rarely, Sometimes, **Often**.	L_{night}, 22:00–6:00 (27.5–62.5)

Table 3. *Cont.*

Study	*N*	Country	Sleep Disturbance Questions	Noise Metric (Range for Obtained Data)
Awakenings–Noise source not specified in sleep questions (*N* = 10,603)				
+ Bodin et al. (2015) [66]	2519	Sweden	Do you wake up at night? Rarely/never, A few times per month, A few times a week, **Almost every day**	L_{Aeq}, 24 h (37.5–62.5)
* Halonen et al. (2012) [67]	6853	Finland	How many times during the past 4 weeks have you had the following symptoms? Frequently waking up during the night. Never, 1 per month, 1 per week, **2–4 per week, 5–6 per week, nearly every night.**	L_{night}, 22:00–7:00 (42.5–57.5)
* Frei et al. (2014) [84]	1231	Switzerland	How often does it happen, that you wake up at night multiple times? Never, Rarely, Sometimes, **Often**.	L_{night}, 22:00–6:00 (27.5–62.5)
Sleep Disturbance-Noise Source not specified in sleep questions (*N* = 9474)				
* Brink (2011) [77]	8245	Switzerland	During the last 4 weeks, have you suffered from any of the following disorders or health problems? Difficulty in sleeping, or insomnia? Not at all, Somewhat, **Very Much**	L_{night}, 22:00–6:00 (32.5–77.5)
* Frei et al. (2014) [84]	1229	Switzerland	How often does it happen that your sleep is restless? Never, Rarely, Sometimes, **Often**	L_{night}, 22:00–6:00 (27.5–62.5)

Table 4. Studies on railway noise and self-reported sleep disturbance (* general health survey, + noise survey). Studies modeled the noise levels except where indicated. Response alternatives contributing to calculation of the percent Highly Sleep Disturbed are in bold.

Study	*N*	Country	Sleep Disturbance Questions	Noise Metric (Range for Obtained Data)
Falling Asleep (Total *N* = 6520)				
+ Bodin et al. (2015) [66]	2342	Sweden	Do you experience any of the following because of railway noise? Difficulties falling asleep? Never, Sometimes, **Often**	L_{Aeq}, 24h (37.5–62.5)
+ Sato et al. (2004) [85]	1418	Hokkaido, Japan	How much are you disturbed in falling asleep by train passing? Not at all, Slightly, Moderately, **Very, Extremely**.	L_{night}, 22:00–7:00, measured (27.5–62.5)
	1562	Kyushu, Japan		L_{night}, 22:00-7:00, measured (27.5-72.5)
+ Schreckenberg (2013) [86]	1198	Germany	To what extent have the following outcomes of railway noise occurred in the past 12 months? Railway noise disturbs when falling asleep. Not at all, Slightly, Moderately, **Very, Extremely**.	L_{night}, 22:00–6:00 (42.5-82.5)
Awakenings (Total *N* = 5311)				
+ Bodin et al. (2015) [66]	2344	Sweden	Do you experience any of the following because of railway noise? You wake up? Never, Sometimes, **Often**	L_{Aeq}, 24h (37.5–62.5)
+ Sato et al. (2004) [85]	1418	Hokkaido, Japan	How much are you disturbed by awakening during nighttime by train passing? Not at all, Slightly, Moderately, **Very, Extremely**.	L_{night}, 22:00–7:00, measured (27.5–62.5)
	1549	Kyushu, Japan		L_{night}, 22:00–7:00, measured (27.5–72.5)
Sleep Disturbance (Total *N* = 1809)				
+ Hong et al. (2010) [82]	610	Korea	How much have you been disturbed in your sleep by railway noise at night when you are sleeping in your house over the last 12 months? 11 point scale used from 0 (not disturbed at all) to 10 (extremely disturbed) **(HSD 8, 9, 10)**	L_{night}, 22:00–7:00 (47.1–70)
+ Schreckenberg (2013) [86]	1199	Germany	To what extent have the following outcomes of railway noise occurred in the past 12 months? Railway disturbs when sleeping during the night. Not at all, Slightly, Moderately, **Very, Extremely**.	L_{night}, 22:00–6:00 (42.5–82.5)

Table 4. *Cont.*

Study	*N*	Country	Sleep Disturbance Questions	Noise Metric (Range for Obtained Data)
Falling Asleep- Noise source not specified in sleep questions (Total *N* = 3808)				
+ Bodin et al. (2015) [66]	2576	Sweden	Do you have problems falling asleep? Rarely/never, A few times per month, A few times a week, **Almost every day**	L_{Aeq}, 24 h (37.5–62.5)
* Frei et al. (2014) [84]	1232	Switzerland	How often does it happen, that you cannot fall asleep well? Never, Rarely, Sometimes, **Often**.	L_{night}, 22:00–6:00 (27.5–57.5)
Awakening-Noise source not specified in sleep questions (Total *N* = 3806)				
+ Bodin et al. (2015) [66]	2575	Sweden	Do you wake up at night? Rarely/never, A few times per month, A few times a week, **Almost every day**	L_{Aeq}, 24 h (37.5–62.5)
* Frei et al. (2014) [84]	1231	Switzerland	How often does it happen, that you wake up at night multiple times? Never, Rarely, Sometimes, **Often**.	L_{night}, 22:00–6:00 (27.5–57.5)
Sleep Disturbance-Noise source not specified in sleep questions (*N* = 5914)				
* Brink (2011) [77]	4685	Switzerland	During the last 4 weeks, have you suffered from any of the following disorders or health problems? Difficulty in sleeping, or insomnia? Not at all, Somewhat, **Very Much**	L_{night}, 22:00–6:00 (32.5–77.5)
* Frei et al. (2014) [84]	1229	Switzerland	How often does it happen that your sleep is restless? Never, Rarely, Sometimes, **Often**	L_{night}, 22:00–6:00 (27.5–57.5)

One line of data was created for each study respondent. For example, if a study had 1000 respondents in the noise category with a 47.5 dB L_{night} midpoint, and 20% were classified as highly sleep disturbed, we generated 800 data lines with non-highly sleep disturbed respondents (binary outcome = 0) and 200 data lines with highly-sleep disturbed respondents (binary outcome = 1). Each data line also carried the mid-point of the 5 dB-wide L_{night} exposure category (data were requested from study PIs that way) and a unique identifier for each study. Random study effect logistic regression models with L_{night} as the only explanatory continuous variable were performed with the NLMIXED procedure in SAS (version 9.3, SAS Institute, Cary, NC, USA). This approach takes into account that respondents were clustered within studies, and the weight of a study increases with its sample size and thus precision. The fixed effect estimates reflect the average study (for a detailed discussion of differences in subject specific and population average modeling approaches see Section S3). The models are based on L_{night} levels between 40 and 65 dBA only. The reason for setting a lower limit of 40 dB is due to inaccuracies of predicting lower noise levels, and 65 dB was chosen for comparability between sources as aircraft noise levels did not exceed this level. Point estimates and 95% confidence intervals were generated with estimate statements in Proc NLMIXED. Analyses were performed separately for each noise source, type of sleep disruption, and whether the question referred specifically to how noise affects sleep. The odds ratios for all outcome measures and noise sources are in Tables 5 and 6. We also calculated a combined estimate of high sleep disturbance across the different survey outcomes (falling asleep, awakenings, sleep disturbance). If a study asked questions on two or three of these outcomes, we averaged the results across outcomes within a study to prevent each subject contributing more than once to the analysis.

Table 5. Unadjusted Odds Ratio for the percent highly sleep disturbed for road, rail, and aircraft noise for questions on falling asleep, awakenings, and sleep disturbance for a 10 dBA increase in L_{night}. L_{night} was treated as a continuous variable from 40 to 65 dBA. Results are for questions that asked how noise affects sleep. Bold font reflects statistically significant results at $p < 0.05$. The combined estimate is based on all sleep questions. The number of subjects contributing to the analyses can be found in Tables 2–4.

	Number of Studies	Odds Ratio per 10 dBA	95% Confidence Interval
Aircraft Noise			
Falling Asleep	6	**2.00**	**1.68–2.41**
Awakenings	5	**1.72**	**1.31–2.27**
Sleep Disturbance	1	**2.05**	**1.64–2.56**
Combined Estimate	6	**1.94**	**1.61–2.33**
Road Noise			
Falling Asleep	8	**2.63**	**1.86–3.73**
Awakening	8	**1.75**	**1.24–2.47**
Sleep Disturbance	3	**2.21**	**1.52–3.20**
Combined Estimate	12	**2.13**	**1.82–2.48**
Rail Noise			
Falling Asleep	4	**2.57**	**1.87–3.53**
Awakening	3	**2.54**	**1.49–4.33**
Sleep Disturbance	2	4.10	0.69–24.41
Combined Estimate	5	**3.06**	**2.38–3.93**

Table 6. Unadjusted Odds Ratio for the percent highly sleep disturbed for road, rail, and aircraft noise for questions on falling asleep, awakenings, and sleep disturbance for a 10 dBA increase in L_{night}. L_{night} was treated as a continuous variable from 40 to 65 dBA. Results are for questions that did not refer to noise in the questions. Bold font reflects statistically significant results at $p < 0.05$. The combined estimate is based on all sleep questions. The number of subjects contributing to the analyses can be found in Tables 2–4.

	Number of Studies	Odds Ratio per 10 dBA	95% Confidence Interval
Aircraft Noise			
Falling Asleep	2	1.10	0.73–1.57
Awakenings	2	0.89	0.66–1.22
Sleep Disturbance	1	4.70	0.41–53.62
Combined Estimate	3	1.17	0.54–2.53
Road Noise			
Falling Asleep	3	1.03	0.77–1.38
Awakenings	3	1.01	0.81–1.25
Sleep Disturbance	2	1.43	0.36–5.59
Combined Estimate	4	1.09	0.94–1.27
Rail Noise			
Falling Asleep	2	**2.02**	**1.44–2.83**
Awakenings	2	1.12	0.90–1.39
Sleep Disturbance	2	1.23	0.85–1.80
Combined Estimate	3	1.27	0.89–1.81

The exposure-response relationships for falling asleep and awakenings for studies that asked about how noise affects sleep are shown in Figure 7. The relationships are not shown individually for questions on sleep disturbance due to the low number of studies. The percent highly sleep disturbed for questions on difficulty falling asleep were higher than the percent highly sleep disturbed calculated based on questions on awakenings. Results for all questions were averaged within each study, and the exposure-response relationships for the combined estimates are shown in Figure 8. For comparison the Miedema and Vos [22] sleep disturbance exposure-response relationships are also shown in Figure 8. For road and rail noise, the percent of the population that was estimated to be highly sleep disturbed was approximately 2% for L_{night} levels of 40 dB. However for aircraft noise 10% of the population was estimated to be highly sleep disturbed for the same noise level. Janssen and Vos [87] derived an updated exposure response curve for the percent highly sleep disturbed for aircraft noise only. This update included studies used by Miedema and Vos that were conducted in the year 1996 or later, and 4 additional studies, two of which are included in this analysis, Brink et al. [76] and Schreckenberg et al. [75]. The aircraft noise exposure-response relationship developed in this analysis and the one derived by Janssen and Vos [87] is shown in Figure 9.

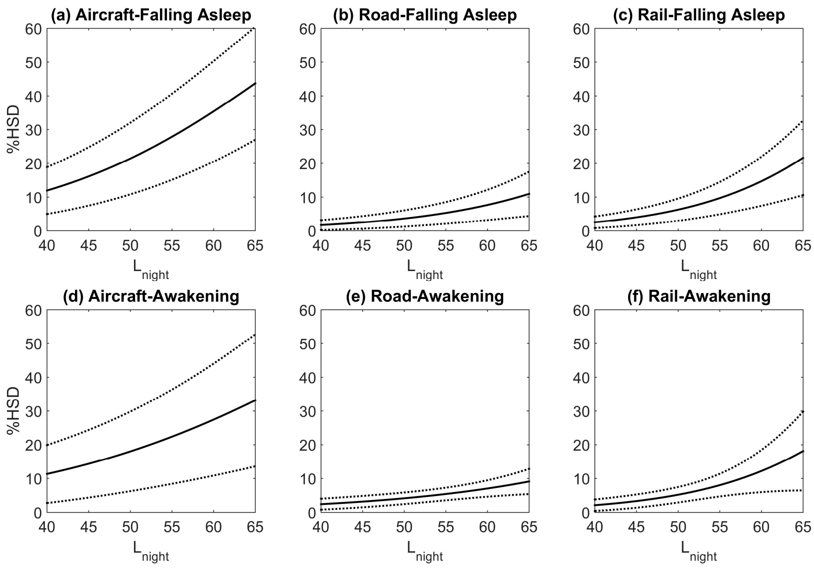

Figure 7. The percent highly sleep disturbed (HSD) based on responses to questions on awakenings or difficulty falling asleep for road, rail, and aircraft noise and for studies that asked about how noise affects sleep (black dashed lines: 95% confidence intervals). The number of studies and subjects contributing to the analyses can be found in Tables 2–4.

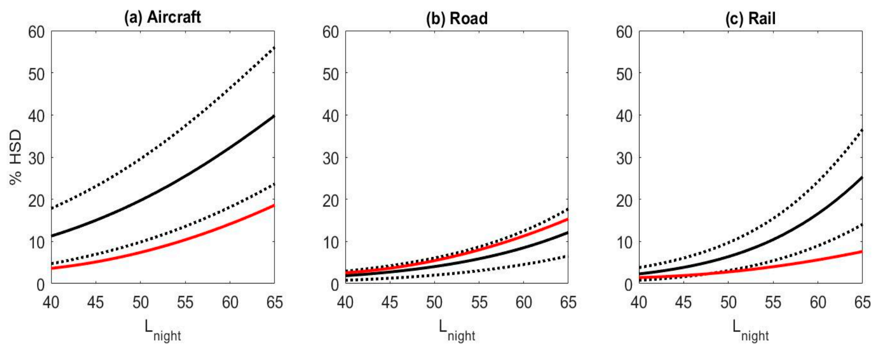

Figure 8. The percent highly sleep disturbed (HSD) based on responses to questions on awakenings, difficulty falling asleep, and sleep disturbance for road, rail, and aircraft noise (black dashed lines: 95% confidence intervals). The number of studies and subjects contributing to the analyses can be found in Tables 2–4. Red: Miedema and Vos (2007) [22] highly sleep disturbed exposure-response curves.

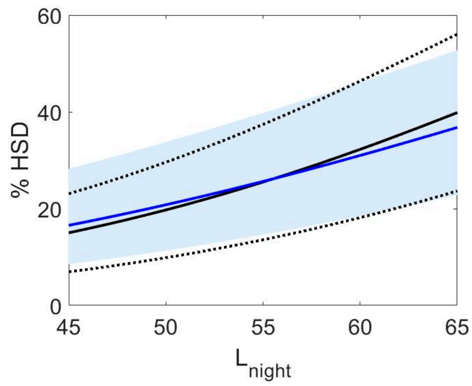

Figure 9. The percent highly sleep disturbed (HSD) based on responses to questions on awakenings, difficulty falling asleep, and sleep disturbance for aircraft noise (black dashed lines: 95% confidence intervals). The number of studies and subjects contributing to the analyses can be found in Table 2. Blue: Janssen and Vos (2009) [87] highly sleep disturbed exposure-response curve.

Second order polynomials were calculated based on the point estimates for the exposure-response relationships for awakenings, difficulty falling asleep, and the combined estimates for questions that asked about the noise source. The equations obtained are as follows (valid for an L_{night} range of 40–65 dB):

For questions on difficulty falling asleep:

$$\text{Aircraft \%HSD} = 16.3369 - 0.9663 * L_{night} + 0.0214 * \left(L_{night}\right)^2 \quad (6)$$

$$\text{Road \%HSD} = 19.3767 - 0.9263 * L_{night} + 0.0122 * (L_{night})^2 \quad (7)$$

$$\text{Train \%HSD} = 44.4836 - 2.1324 * L_{night} + 0.0273 * (L_{night})^2 \quad (8)$$

For questions on awakenings:

$$\text{Aircraft \%HSD} = 12.0411 - 0.5646 * L_{night} + 0.0137 * (L_{night})^2 \quad (9)$$

$$\text{Road \%HSD} = 8.8986 - 0.4209 * L_{night} + 0.0065 * (L_{night})^2 \quad (10)$$

$$\text{Train \%HSD} = 38.5819 - 1.8376 * L_{night} + 0.0234 * (L_{night})^2 \quad (11)$$

For the combined estimates:

$$\text{Aircraft \%HSD} = 16.7885 - 0.9293 * L_{night} + 0.0198 * (L_{night})^2 \quad (12)$$

$$\text{Road \%HSD} = 19.4312 - 0.9336 * L_{night} + 0.0126 * (L_{night})^2 \quad (13)$$

$$\text{Train \%HSD} = 67.5406 - 3.1852 * L_{night} + 0.0391 * (L_{night})^2 \quad (14)$$

In addition to the analyses based on individual response data presented above, we also calculated the unadjusted odds ratio per 10 dBA increase in L_{night} for each individual study (using the combined estimate) and derived pooled estimates across studies for each transportation mode with the Review Manager Software (RevMan, Version 5.3, Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014). L_{night} was treated as a continuous variable and its range was not restricted for calculating individual study estimates. The purpose of this analysis was primarily to assess the heterogeneity of the studies. The results are shown in Figures 10–12. The small differences between pooled estimates provided in Tables 5 and 6 and Figures 10–12 are expected due to the different underlying methodological approaches (random study effect model estimate based on individual response data versus pooled estimate across individual study estimates).

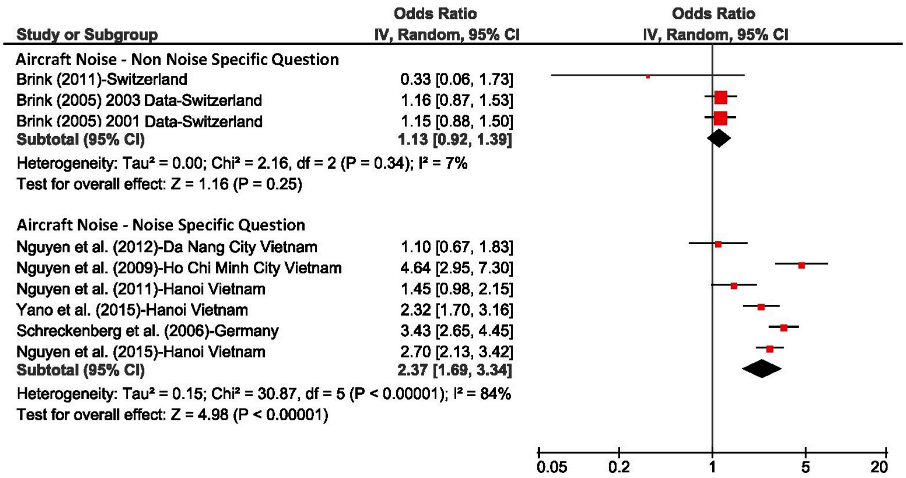

Figure 10. Meta-analysis on the effects of aircraft noise on self-reported sleep disturbance (combined estimate) based on Odds Ratios for a 10 dBA increase in L_{night} level for aircraft noise. The number of studies and subjects contributing to the analyses can be found in Table 2.

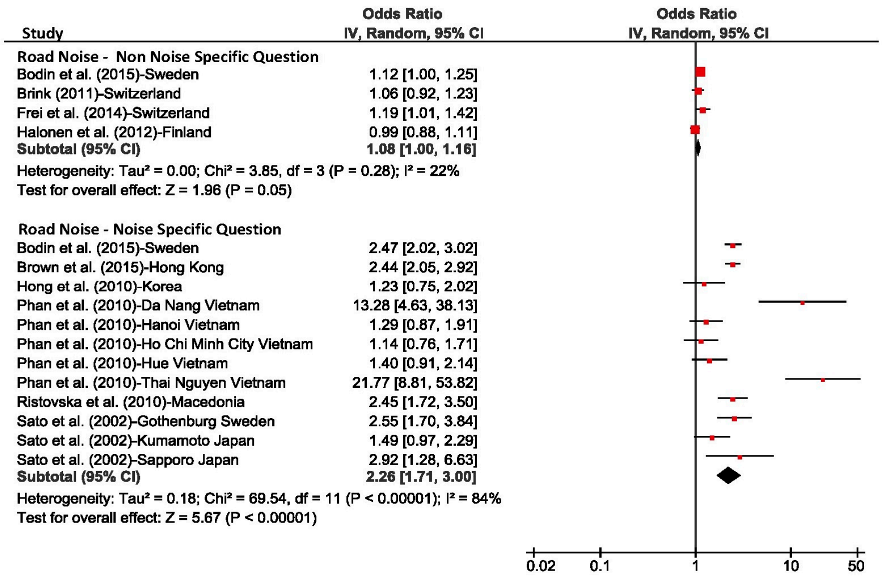

Figure 11. Meta-analysis on the effects of road noise on self-reported sleep disturbance (combined estimate) based on Odds Ratios for a 10 dBA increase in L_{night} level for road noise. The number of studies and subjects contributing to the analyses can be found in Table 3.

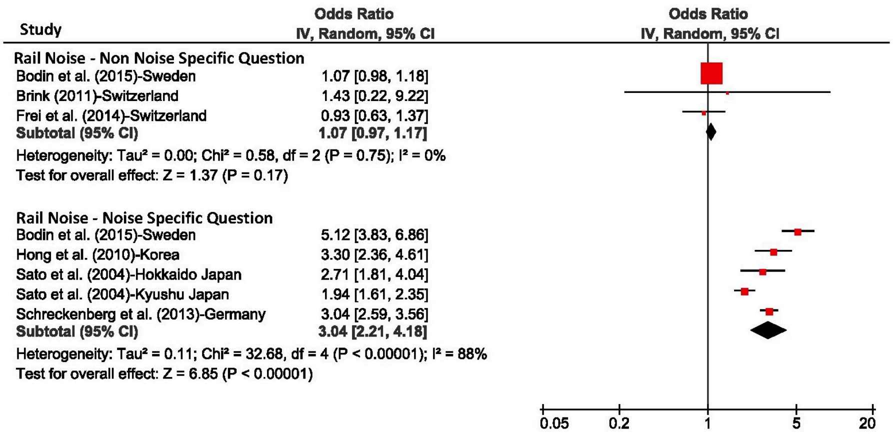

Figure 12. Meta-analysis on the effects of rail noise on self-reported sleep disturbance (combined estimate) based on Odds Ratios for a 10 dBA increase in L_{night} level for rail noise. The number of studies and subjects contributing to the analyses can be found in Table 4.

The I^2 values, a measure of variance across studies, was 84% for road and aircraft noise studies that mentioned the noise source in the sleep question, and was 88% for train noise which indicates there was high heterogeneity between studies. In contrast, for studies that did not refer to the noise source, the I^2 values were 22% or lower, however the number of studies for these meta-analyses were low.

4.2. Additional Studies

Results from studies that were not included in the meta-analysis are listed in Table S1. The reason for exclusion of these studies include: the aggregated response data was not available and that the sleep question used had only a binary response choice. Our meta-analysis without these studies is unlikely to be biased in showing a positive association between noise level and percent highly sleep disturbed as only one study by Ohrström et al. (2010) [88] found no association between self-reported sleep disturbance and train noise. However if these studies were included in the meta-analysis they may have affected the magnitude of the effect that was found.

4.3. Conclusions

Noise is only one reason for sleep disturbance. There are many other external (e.g., temperature, humidity, light levels) and internal (e.g., sleep disorders, health conditions, bad dreams) causes. For this reason, odds ratios for sleep disturbance were calculated separately for those studies that did and did not ask about sleep disturbance, awakenings, or problems falling asleep relative to a specific noise-source. The odds ratios calculated for all noise sources and sleep outcomes were greater than 1 but not statistically significant when the noise source was not specifically mentioned in the question except in one case. However, odds ratios were much higher and mostly statistically significantly different from 1 when the noise source was mentioned in the question. This difference could be due to lack of adjustment for confounding factors in the analysis, such as age, gender, socio-economic status, and pre-existing sleep or health conditions. However, the context and wording of the questions can also bias the results.

The surveys included in this meta-analysis consisted of both noise surveys and general health surveys which contained questions on sleep. Bodin et al. [89] examined whether response to questions on the effects of road traffic and train noise was dependent on the context of the survey, whether the survey was presented as a noise and health survey. The question on sleep asked how often sleep was disturbed. The percent of the population providing response alternatives at the end of the scale (i.e., "Every day" and "Never") was the same when the questions were presented as a noise survey and when they were presented as a more general survey.

In the studies examined in this meta-analysis the type of questions asked were also different, with some studies referring specifically to how noise affects sleep while other studies contained more general sleep questions. Barker and Tarnopolsky (1978) [90] examined the difference in response to noise specific and non-noise specific questions in two groups of people exposed to high and low levels of aircraft noise. They asked two questions in their study, one question asked if participants had been nervous and irritable and the other asked if aircraft noise made them feel nervous or irritable. When the question did not refer to noise the percent reporting symptoms was not significantly different between the high noise and low noise exposure group. However there was a significant difference between the two exposure groups when the question referred to noise, which is consistent with the findings of our meta-analyses. For the studies used in this review, even when questions referred to the noise source and the same sleep outcome measure, there were additional differences in the specific wording, reference time frame, and response format of the sleep questions. For example, some studies referred to sleep disturbance during the past 12 months, others during the past month, and a few studies referred to single events or no time period at all. These differences could have all contributed to the high heterogeneity found between studies.

Despite the differences in sleep questions used, results were averaged across questions within studies to obtain combined estimates. These estimates were compared to the previous models developed by Miedema and Vos (2007) [22]. In contrast to their analysis our meta-analysis found that the percent highly sleep disturbed was greater for railway noise than for road noise. In addition, for both rail and aircraft noise the percent highly sleep disturbed was higher in this analysis than Miedema and Vos's. This difference could be due to different methodologies used to derive the model. Also many of the studies included in this meta-analysis were conducted in Japan and Vietnam where the noise exposure and attitude towards noise may be different than in European countries. In addition, in Miedema and Vos's analysis the questions referred to annoyance that occurred due to sleep disturbance for several of the studies, while in this analysis the questions were on the severity or frequency of sleep disturbance. Also, in the studies included on train noise in this analysis, more nighttime events were reported than in previous studies [86].

Another potential difference for the findings in this analysis and Miedema and Vos's is that this analysis only contained studies published in the year 2000 or later. Recent updates to annoyance exposure-response curves have found an increase in annoyance although only for aircraft noise [91]. The higher reported sleep disturbance found in this analysis is also consistent with the updated exposure-response curve reported by Janssen and Vos [87] for aircraft noise which only included studies conducted in 1996 or later.

Limitations of the current meta-analysis include that L_{night} was predicted or measured at the most exposed façade only, and thus noise levels at the bedroom façade were unknown. The potential effect on the results is likely dependent on the noise source, and could be more important for the results for road and train noise but less for aircraft noise due to the directionality of the noise. Ultimately, this misclassification could result in a shift in the exposure-response curves for road and rail noise to the left, as noise levels in the bedroom are on average likely lower compared to the most exposed façade. Also two of the studies included in the meta-analysis did occur after a change in noise level. The Nguyen et al. [69] aircraft study occurred after the opening of a new terminal building. The average nighttime noise levels did increase for 9 of the 11 sites. However the mean increase in L_{night} was 2 dB; in addition there was a non-significant difference in the Odds Ratio when compared to the results from the Yano et al. [70] study that was conducted before the new terminal was opened. Therefore we included the data in the analysis. Brink et al. [76] conducted 2 surveys before and after a change in operations at Zurich airport, the results from both studies were included in the evidence review as the odds ratios for an increase in sleep disturbance for the two studies were not significantly different.

5. Wind Turbine Noise and Self-Reported and Actigraphy Measured Sleep Outcomes

5.1. Literature Review

Six studies were identified in the literature review in which the association between predicted A-weighted sound pressure levels of wind-turbine noise and self-reported measures of sleep disturbance were assessed. For three of the studies the questions asked how noise affects sleep. Two of the studies were conducted in Sweden [92,93] and one in the Netherlands [94]. For the two studies conducted in Sweden sleep disturbance was assessed using a binary question which asked whether sleep was disturbed by any noise source, while the study conducted in the Netherlands asked how often sleep was disturbed by any noise source with a frequency of at least once a month considered sleep disturbance. The odds ratios for sleep disturbance per 1 dB increase in the predicted A-weighted sound pressure level for all three studies was reported in Pedersen 2011 [48], the values transformed for a 10 dBA increase in noise level can be found in Table 7. For two of the studies a significant association was found between wind turbine noise levels and sleep disturbance. In addition, the Dutch study by Bakker et al. (2012) [94] reported a significant Odds Ratio for sleep disturbance when comparing individuals exposed to noise levels above 45 dBA to those exposed to noise levels less than 30 dBA (2.98, 95% CI: 1.35–6.60). However, in their structural equation model, they found that annoyance was the only factor that predicted sleep disturbance.

For the three remaining studies the effect of wind turbine noise on sleep was evaluated using questions that did not refer to noise. Pawlaczyk-Luszcynsa et al. [95] conducted a study in 2011 in Poland which included questions on different aspects of sleep including difficulty falling asleep. They found that the proportion of individuals reporting that they suffer from sleep disturbance at least a few times per week was significantly higher in individuals exposed to wind turbine noise levels of 40–45 dBA compared to those exposed to levels of 35–40 dBA (26% vs. 10.2%, $p < 0.05$). Kuwano et al. [96] examined self-reported insomnia in a study conducted in Japan. This study included both a noise exposed and control group. Insomnia was defined as having difficulty falling asleep, maintaining sleep, prematurely awakening, or having light sleep at least 3 times a week for any reason. The insomnia prevalence rate in the study was low, with 3.1% of participants exposed to 41–45 dB L_{night} and 2.7% of participants exposed to an L_{night} of greater than 45 dB reporting insomnia. Kuwano et al. also stratified their data according to those individuals who were noise sensitive or not noise sensitive and a significant association between insomnia and L_{night} was only found in the noise sensitive population, though this analysis is limited due to the very low insomnia prevalence rate in the study. Also in contradiction to this finding, Pedersen and Persson-Waye [92] found no association between noise sensitivity and reported sleep disturbance. Michaud [97] assessed subjective and objective measures of sleep for those exposed to predicted wind turbine noise levels of up to 46 dB in Canada. In total 1238 households completed subjective assessments which included the Pittsburgh Sleep Quality Index. No association was found between the mean value of PSQI and wind turbine noise levels or between the percent of participants with a score of 5 or higher and the noise levels. Michaud also evaluated whether individuals were highly sleep disturbed, and found no significant association with wind turbine noise levels.

A meta-analysis was conducted for five of the six studies based on the odds ratios for sleep disturbance for a 10 dBA increase in outdoor predicted SPL levels. The results are shown in Figure 13. The analysis was performed separately for questions that did and did not mention noise in the questions on sleep. The pooled odds ratio was 1.60 (95% CI: 0.86–2.94) which was statistically non-significant, there was also high heterogeneity between studies with an I^2 value of 86%.

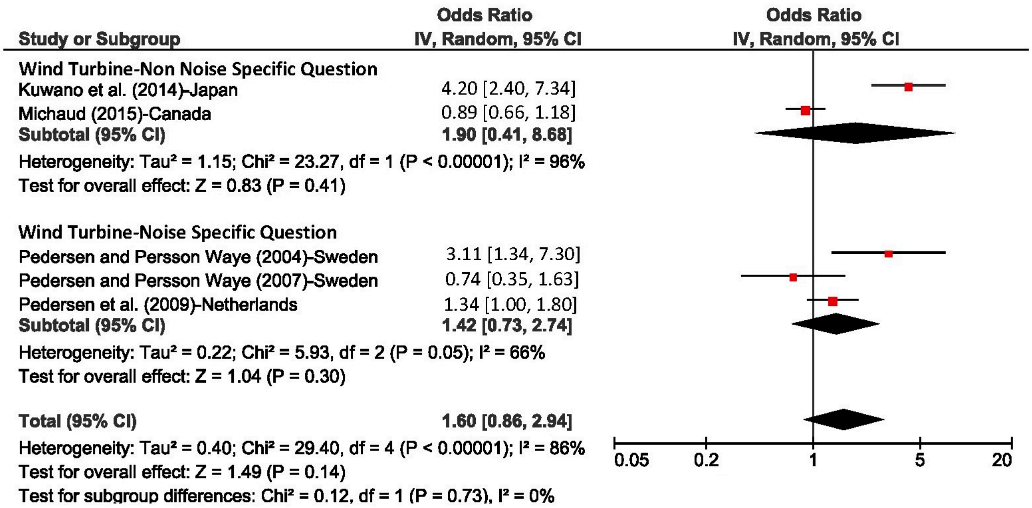

Figure 13. Meta-analysis on the effects of wind turbine noise on self-reported sleep disturbance based on Odds Ratios for a 10 dBA increase in A-weighted SPL level for wind turbine noise. The number of subjects contributing to the analyses can be found in Table 7.

5.2. Conclusions

The results of the six identified studies that measured self-reported sleep disturbance are consistent, four of the studies found an association between wind turbine noise levels and increased sleep disturbance. However the evidence that wind turbine noise affects sleep is still limited. This finding is supported by other recent reviews on wind turbine noise and sleep disturbance [56,98,99]. Three of the studies referred to noise specifically in the questions which could have led to a bias in the results. Also while the results from four out of the six studies suggest that sleep disturbance due to wind turbine may occur when noise levels are above 40 or 45 dBA, for two of the studies less than ten percent of the participants were exposed to these higher noise levels. Therefore, it is difficult to make conclusions on populations exposed to these higher levels. In addition, noise levels were calculated using different methods and different noise metrics were reported in the studies. Pawlaczyk-Luszcynsa et al. [95] reported L_{den} levels which were obtained by adding a +4.7 dBA correction to the predicted sound pressure levels. In the Kuwano et al. [96] study wind turbine noise was measured at select locations, and then a logarithmic regression was performed between the measured noise levels and distance from the wind turbines. Noise levels for each participant were estimated based on the regression which could have led to misclassification. While noise level measurements were made to confirm noise predictions in a few studies, noise levels were never measured inside participant's bedrooms. The audibility of wind turbine noise in bedrooms particularly when windows are closed is unknown. In the study by Pedersen and Persson Waye [92] all but two of 20 subjects that reported sleep disturbance slept with open windows.

Evidence is also limited as five of the six studies only obtained self-reported measures of sleep disturbance. There have been two studies which used actigraphy to evaluate sleep due to wind turbine noise. In a study by Lane [100] 13 individuals slept for five consecutive nights while wearing actigraphy devices. The sample size was too small to draw significant conclusions. Actigraphy was also used to evaluate sleep for multiple nights in a subsample of 654 participants in a study by Michaud [97]. They found no significant association between wind turbine noise levels and actigraphy measured outcomes, but predicted L_{night} levels did not exceed 46 dBA outside with an arithmetic mean of 35.6 dBA for the study population. Studies using both objective measures of sleep and noise exposure are still needed.

Table 7. Characteristics of studies on self-reported measures of sleep disturbance and wind turbine noise. Odds ratios for sleep disturbance are listed.

Reference	Country	N	N (>40 dBA)	Noise Exposure	Confounding Variables Adjusted for in the Statistical Analysis	Odds Ratio per 10 dBA (95% CI)	Odds Ratio Relative to Reference (95% CI)
Pedersen and Persson Waye (2004) [92]	Sweden	351	25	Predicted A-weighted SPL	Age, gender	3.11 (1.34–7.30)	Reference: <35 dBA >35 dBA: 4.72 (0.27–82.97)
Pedersen and Persson Waye, (2007) [93]	Sweden	754	20	Predicted A-weighted SPL	Age, gender	0.74 (0.35–1.63)	NA
Pedersen et al. (2009) [101] Bakker et al. (2012) [94]	Netherlands	725	159	Predicted A-weighted SPL	Age, gender, economic benefits	1.34 (1.00–1.80)	Reference <30 dBA >45 dBA: 2.98 (1.35–6.60)
Kuwano et al. (2014) [96]	Japan	747 (332 Controls)	260	L_{night} (22:00-6:00)	Age, gender	4.20 (2.40–7.34)	Reference: <35 dBA 41–45 dBA: 5.55 (1.12–27.47) >46 dBA: 4.79 (0.64–35.70)
Michaud (2015) [97]	Canada	1238	234	Predicted A-weighted SPL	None	0.89 (0.66–1.18)	NA
Pawlaczyk-Luszcynsa et al. (2014) [95]	Poland	156	90	L_{den}	None	NA	Reference: 35–40 dBA 40–45 dBA: 2.74 (1.08–6.97)

6. Hospital Noise

6.1. Literature Review

Seventeen studies were identified in which the effects of hospital noise on sleep were examined. Five were intervention studies in which quiet hours were implemented to reduce noise. While intervention studies are covered in another review, we included them here due to the low number of studies on hospital noise and sleep that were identified. Also it may be difficult to observe a wide variance in noise levels within a study in the same hospital ward without implementing an intervention. Of the non-intervention studies, nine examined the effect of noise on sleep in adult patients and three studies examined the effect on young children. Characteristics for all studies reviewed are shown in Tables 8–10. The study methodology was too diverse and prohibited us from doing a systematic meta-analysis. Of the studies in adults, four compared arousals measured with polysomnography to peaks in noise level. Aaron et al. (1996) [102] found a significant correlation between arousals and noise events which exceeded 80 dBA ($r = 0.57$, $p = 0.0001$) in a small study of six patients. However, in a study by Elliott et al. (2013) [103] which used a similar methodology but enrolled 53 patients, only a weak non-significant correlation between arousals and noise events was found (daytime measurements: $r = 0.13$; nighttime measurements $r = 0.19$). Freedman et al. (2001) [104] reported that 11.5% $\pm$ 11.8% of arousals in patients were due to noise events. Gabor et al. (2003) [105] examined sleep in both patients and healthy individuals who slept in the Intensive Care Unit and found that while 68.4% of arousals in healthy individuals were related to noise events only 17.5% of arousals in patients were. Three of the studies reviewed used actigraphy to evaluate measures of sleep duration and efficiency. Adachi et al. (2013) [106] found no association between hourly minimum noise levels and sleep duration. Missildine et al. (2010) [107] found no association between sleep efficiency and mean noise levels. However, Yoder et al. (2012) [108] did find that those exposed to the loudest tertile of average nighttime noise levels slept significantly less than those exposed to the quietest tertile.

Of the three studies identified that examined sleep in children, two of the studies, Corser (1996) [109] and Cureton-Lane and Fontaine (1997) [110], evaluated sleep subjectively using the Patient Sleep Behavior Observation Tool (Echols, 1968) [111] which describes patient behaviors that are related to 4 levels of cortical activity. Corser (1996) [109] found a small correlation between noise levels and observed sleep state ($r = -0.20$, $p < 0.05$) in infants (mean age 23.3 months). The observed sleep state though was more strongly correlated to behavioral indicators of pain ($r = -0.27$, $p < 0.05$) and caregiver activities ($r = -0.30$, $p < 0.05$). Similar results were found by Cureton-Lane and Fontaine [110]. In a probit analysis, noise was a significant predictor of sleep state in children (mean age 4.7 years). However, light levels and caregiver activity were also identified as significant predictors. Kuhn et al. [112,113] used both subjective and objective measures of sleep; the objective measurements included heart rate, blood pressure and respiration rate. They found that respiration rate significantly decreased during quiet sleep in pre-term infants when a noise event exceeded the background level by 10 dBA (-10.0 ± 12.5 breaths/min, $p = 0.002$).

Several of the studies examined whether interventions to reduce noise resulted in improved sleep. Dennis et al. (2010) [114] implemented a two hour quiet period during the day and night in which telephone volumes were decreased, caregiving activities were reduced, visiting hours were limited, and the staff were encouraged to interact quietly. During the day the implementation of quiet hours resulted in a 9 dB reduction in noise level (71.2 dB prior to the intervention, 62.2 dB during the intervention) while at night only a 1.4 dB reduction occurred. Sleep state was determined based on observation every 30 min. A significant Odds Ratio for being asleep was found when the intervention was implemented during the day (4.04, 97.5% CI 2.24–7.30) however, not when it was implemented during the night (0.96, 97.5% CI 0.41–2.24). Gardner et al. (2009) [115] implemented a quiet period during the daytime only and included both an experimental and control group. While they found a significant correlation between noise levels and the number of patients observed to be awake in the experimental group ($r = 0.704$, $p \leq 0.01$) the correlation in the control group was weak ($r = 0.24$, $p < 0.05$).

Therefore, it is unclear whether it was the reduction in noise level that resulted in more of the patients being observed asleep. Walder et al. (2000) [116] found results that were opposite to the previous studies, they found that sleep duration and the number of awakenings was greater after behavioral rules to reduce noise were implemented. However, the same patients did not take part before and after the intervention was implemented, also the number of patients enrolled was small. Contrary to previous studies, Thomas et al. (2012) [117] did not find an improvement in noise levels when sleep promoting measures were put into practice; however the noise levels were low, below 40 dB before the intervention. One intervention study was conducted with children. Duran et al. (2012) [118] conducted a study to examine whether preterm infants that wore earmuffs while in an incubator, which reduced noise levels by 7–12 dBA, had improved heart rate, respiration rate, and blood pressure, and subjective observations of sleep. They found that more infants were observed in a state of rest when wearing the earmuffs (87.5% with ear muffs, 29.4% without earmuffs). However no difference was found in the physiological measurements. Both subjective and objective measurements were recorded once every two hours.

6.2. Conclusions

Sleep quality in hospitals in general is low. Studies have found that sleep primarily consists of Stage 1 and 2 sleep with low or absent amounts of REM and slow-wave sleep [104,119]. In addition average sleep bouts of 20 min duration or less have been measured [107]. Sleep disturbance in hospitals can be caused by many factors including pain, medication, desynchrony with ventilation, care-giving activities, stress, unfamiliar environment, in addition to environmental factors such as light and noise levels. While noise is just one component, the average noise levels in the studies reviewed were high, with L_{day}, L_{night}, and $L_{eq,24hr}$ primarily above 50 dBA [103,105,110], with several reporting noise levels exceeding 60 dBA [115,120,121].

Despite the high noise levels the quality of the evidence on the effect of noise on sleep is low. The results of 14 studies do indicate that noise is among the factors contributing to sleep disturbance in hospitals. The results from the four studies that used polysomnography indicate there is a weak correlation between EEG arousals and events of high noise level and that 10–20% of all arousals maybe associated with noise events. The results from studies using actigraphy measures of sleep however were contradictory with only one study finding a significant association between noise and sleep duration. In children, the study by Kuhn et al. [112,113] did find that increases in noise level affected physiological measures of pre-term infants. Also in two of the four studies, implementing quiet hours in adults, lower noise levels and improved sleep were found. The relationship between noise levels or signal-to-noise ratios and the likelihood of having a physiological reaction to the noise events though is unclear based on the studies reviewed.

Another limitation of the studies reviewed is that several only examined correlations and confounding factors were not adequately examined. A study by Park et al. (2014) [120] though did include several important confounders in their analysis. They measured subjective sleep quality using the Pittsburgh Sleep Quality Index [122] and found that sleep disturbance scores increased with mean daytime and nighttime noise levels even after controlling for age, gender, severity of disease, medication, and room-type. Additional factors that should be examined include mechanical ventilation and time in unit. The length of time spent in the hospital could be examined as a confounding variable or as an outcome measure as it may increase when there are higher noise levels.

Table 8. Characteristics of studies on hospital noise and sleep in adults.

Reference	N	Age	Hospital Unit	Noise Measurement	Subjective Measure	Objective Measure	Outcome
Aaron et al. 1996 [102]	6	66.8 ± 2.8 years	Intensive and Intermediate Respiratory Care Unit	SPL every minute	NA	Polysomnography	Correlation (r = 0.57, p = 0.0001) between number of arousals (between 22:00–6:00) and SPL peaks ≥ 80 dB
Adachi et al. 2013 [106]	118	65.0 ± 11.6 years	General Medicine	Hourly L_{min}, L_{eq}, L_{max}	Karolinska Sleep Log	Actigraphy	Multivariate linear and logistic regressions: No significant association between L_{min} tertiles and sleep duration, Karolinska Sleep Quality, or noise complaints
Elliott et al. 2013 [103]	53	60.1 ± 20.0 years	Intensive Care Unit	L_{Aeq} and L_{Cpeak} levels logged every second	Richards Campbell Sleep Questionnaire	Polysomnography	Weak correlation between arousal indices and number of sound peaks > 80 dB (day r = 0.13, night r = 0.19)
Gabor et al. 2003 [105]	13 Patients: 7 Control: 6	Patients: 56. 7± 19.2 years Controls: 23–65 years	Intensive Care Unit	SPL	NA	Polysomnography	17.5 ± 11.2% (Patients) and 68.4 ± 11.1% (Control Subjects) of arousals were associated with a sound event greater than 10 dB over background
Freedman et al. 2001 [104]	22	61 ± 16 years	Intensive Care Unit	SPL every minute	NA	Polysomnography	11.5 ± 11.8% of arousals and 26.2 ± 24.8% of awakenings was due to environmental noise
Hsu et al. 2010 [121]	40	54. 5± 14.5 years	Cardiac Surgical Unit	SPL every second	Questions on insomnia	Heart rate and blood pressure every 5 min	Correlation between insomnia and noise level, L_{eq} (r = 0.09), L_{max} (r = 0.24), L_{min} (r = −0.03).
Missildine et al. 2010 [107]	48	79 years	Medical Unit	SPL levels (23:00–7:00)	Richards Campbell Sleep Questionnaire	Actigraphy	For those subjects with less than 300 minof sleep, 59% were exposed to nighttime noise levels ≥ 40 dBA. In a multiple regression for sleep efficiency, the coefficient for median noise level was not significant (β = −0.671, p = 0.836).
Park et al. 2014 [120]	103	60 ± 14.8 years	Internal Medicine	Leq	Pittsburgh Sleep Quality Index	NA	Sleep disturbance scores increased with mean daytime and nighttime levels (β = 0.2; 95% CI = 0.09–0.53 for daytime; β = 0.12; 95% CI = 0.07–0.36 for nighttime). Controlled for age, gender, severity of disease, medication, and room type.
Yoder et al. 2012 [108]	106	66.0 ± 12 years	General Medicine	L_{min}, L_{eq}, L_{max}	Pittsburgh Sleep Quality Index	Actigraphy	Patients exposed to the loudest tertile of average nighttime noise levels slept significantly less (−76 min, 95% CI −134 to −18 min, p = 0.01) than patients exposed to the lowest tertile of noise.

Table 9. Characteristics of studies on hospital noise and sleep in children.

Study	N	Age	Hospital Unit	Measure of Noise	Subjective Measure	Objective Measure	Outcome
Corser 1996 [109]	12	23.3 ± 6.1 months	Pediatric Intensive Care Unit	SPL every 5 min	Patient Sleep Behavior Observation Tool used to identify sleep state every 5 min 19:00–7:00	NA	Correlation between observed sleep state and noise ($r = -0.2043$, $p < 0.05$).
Cureton-Lane and Fontaine 1997 [110]	9	4.7 ± 3.5 years	Pediatric Intensive Care Unit	SPL every 5 min	Patient Sleep Behavior Observation Tool used to identify sleep stage every 5 min from 20:00–6:00	NA	Noise was a significant predictor of sleep state in probit analysis ($p < 0.001$). Light levels and contact with staff were also significant predictors.
Kuhn et al. 2013 [112] Kuhn et al. 2012 [113]	26	28 weeks (median)	Neonatal Intensive Care Unit	Classified sound peaks: those exceeding the previous level by more than 5 dBA	Prechtl's observational rating system for defining arousal states.	Heart Rate, Respiratory Rate and SaO_2	Average percent awakened due to classified sound peaks was 33.8% (95% CI: 24–37%). For control periods without sound peaks average percent awakened was 11.7% (95% CI: 6.2–17.1%). For sound peaks 10–15 dBA above background a significant decrease in respiration rate (−10 ± 12.5 breath/min, $p = 0.002$) during quiet sleep was found.

Table 10. Characteristics of intervention studies on hospital noise and sleep in adults and children.

Study	N	Age	Hospital Unit	Invention	Measure of Noise	Subjective Measure	Objective Measure	Outcome
Dennis et al. 2010 [114]	50 Day: 35 Night: 15	Day: 55.5 ± 14.4 years Night: 52.9 ± 16.3 years	Neuro-Intensive Care Unit	Implemented 2 h quiet period during the day and night	SPL collected 6 times a day over a period of 5 s before, after and during the quiet time hours	Sleep Observation Tool: seven observations made per subject	NA	Odds Ratio (97.5% CI) observed asleep: Day: 4.04 (2.24–7.30) Night: 0.96 (0.41–2.24)
Duran et al. 2012 [118]	20	30.0 ± 2.2 weeks	Neonatal Intensive Care Unit	Infants wore earmuffs that decreased noise levels by 7–12 dBA for 2 days	Measurements made every 2 h during an 8 h period	Anderson Behavioral State Scoring System. Measurements made every 2 h during an 8 h period	Blood pressure, heart rate, respiration rate, body temperature, and oxygen saturation. Measurements made every 2 h during an 8 h period	For the two conditions (with and without earmuffs): No difference was observed in physiological measures. 87.5% of infants with earmuffs observed asleep, 29.4% of infants without earmuffs observed asleep
Gardner et al. 2009 [115]	293 Experimental: 137 Control Group: 156	Experimental Group: 56.4 ± 19.1 years Control Group: 50.5 ± 19.4 years	Orthopedic Unit	Implemented quiet hours	Daily SPL	Observed Sleep State	NA	Correlation between mean SPL levels and patients found to be awake: Experimental: ($r = 0.704$, $p < 0.01$) Control group: $r = 0.243$, $p < 0.05$)
Thomas et al. 2012 [117]	95 Phase 1: 32 Phase 2: 33 Phase 3: 30	Phase 1: 49 ± 1 years Phase 2: 43 ± 3 years Phase 3: 46 ± 3 years	Neurological Unit	Study had 3 phases with measured noise levels Phase 2: Sleep promoting rules	SPL between 20:00–8:00	Questions on sleep quality, sleep quantity	NA	Intervention did not result in a reduction in noise level. The median noise levels were: Phase 1: 38.6 dB, Phase 2: 40.6 dB, Phase 3: 43.5 dB
Walder et al. 2000 [116]	17 Before Guidelines: 9 After Guidelines: 8	Before Guidelines: 62.5 ±16.5 years After Guidelines: 57.8 ±15.9 years	Surgical Intensive Care Unit	Implemented behavioral rules	SPL, every 1 s between 23:00–5:00.	Nurses estimated the patient's sleep duration and the number of awakenings.	NA	Sleep duration was shorter, and the number of awakenings higher when the behavioral rules were implemented.

7. Additional Sleep Outcome Measures

7.1. Cardiac and Blood Pressure Outcome Measures during Sleep in Adults

In this review, while several studies were identified in which electrocardiogram (ECG) measurements were performed [35,60–62] only two studies were identified in which the results on the effects of transportation noise on cardiac measures and blood pressure were reported. Haralabidis et al. (2008) [123] examined the effect of road and aircraft noise on heart rate and blood pressure measurements as part of the HYENA study. 140 subjects underwent 24 h ambulatory blood pressure measurements with heart rate, measurements were recorded every 15 min. Noise levels within the bedroom were also recorded. When aircraft events occurred a small but significant increase in both systolic and diastolic blood pressure was found for a 5 dB increase in indoor maximum noise level (systolic: 0.66 mmHg, 95% CI 0.33–0.98 and diastolic: 0.64 mmHg, 95% CI 0.37–0.90). For road traffic noise a small but significant increase in blood pressure was also found (systolic: 0.81 mmHg, 95% CI 0.46–1.16 and diastolic: 0.55 mmHg, 95% CI 0.26–0.83). Graham et al. (2009) [124] examined respiratory sinus arrhythmia and pre-ejection period in 36 subjects exposed to road and rail noise. Respiratory sinus arrhythmia was considered an index for cardiac parasympathetic tone and pre-ejection period was considered an index of cardiac sympathetic tone. No significant association was found between pre-ejection period and the average indoor noise level during the sleep period. A significant decrease of the log of respiratory sinus arrhythmia with noise level was found, with age as a significant covariate. This finding suggests that noise exposure may lead to decreased parasympathetic tone.

7.2. Motility Measured Sleep Outcomes in Adults

Eight studies were identified in which motility was measured (see Table 11). Four of the studies examined the probability of having a motility reaction due to single noise events. In a study by Passchier-Vermeer et al. (2002) [64] 418 individuals that lived near Schiphol airport wore actigraphs continuously for 11 days. They found a significant increase in motility reaction with the indoor maximum noise level ($L_{AS,max}$) of aircraft events. The estimated probability of a motility reaction was less than 1% for events of 40 dB, and was greater than 4% for events of 60 dB. In 2007, Passchier-Vermeer et al. conducted a second study to examine the effect of road and rail noise on measures of motility. The study included 262 participants who wore actigraphs for 5 consecutive nights. They found that motility and motility onset increased with noise level, and that railway noise did not have a greater effect on motility than road traffic noise. Hong et al. (2006) [125] also used actigraphs to evaluate sleep in 12 subjects exposed to railway noise. They found slightly higher probability of reaction then found in the Passchier-Vermeer et al. [64] study. Lercher et al. (2010) [126] used seismosomnography [127] to measure movement in individuals exposed to rail noise. In a linear regression, for the probability of motility, the coefficient for L_{Amax} was significant (0.04 per dB, 95% CI 0.01–0.07, $p < 0.01$).

For the remaining 4 studies, actigraphy derived sleep parameters for the entire night were compared to average noise levels. Ohrström et al. (2006) [128] conducted a study using actigraphy in both children and their parents. No clear exposure-response relationship was found between mean activity, wake episodes, and sleep latency and predicted $L_{Aeq,24hr}$ for the parents. Frei et al. (2014) [84] did not find a significant decrease in sleep duration with predicted outdoor L_{night} levels. However, sleep efficiency was found to decrease with L_{night} even after adjusting for several confounding variables including gender, age, education, and body mass index. Unlike the two previous studies Pirrera et al. (2014) [129] recorded noise levels within the bedroom of participants. The study consisted of two groups, 23 individuals that lived in an area with high levels of road traffic and 22 individuals that lived in a more quiet area. There was a 10 dB difference in the mean outdoor L_{Aeq} (measured during the participant's time in bed period) between the high and low noise group, however there was not a significant difference in the indoor L_{Aeq} levels between the two groups. Therefore although individuals in the high noise group spent less time in bed (high noise group: 433 min, quiet group: 451 min), there was no significant difference found in sleep onset latency, wake after sleep onset, or sleep efficiency. Griefahn et al. (2000) [130], similar to the other studies mentioned, found no association between road and rail noise levels and motility. The results from motility studies are therefore conflicting in that there is evidence from 4 of the 8 studies that for single-events there is an increase in movement. On the other hand, there is not consistent evidence that sleep parameters descriptive of the entire night are affected by noise.

Table 11. Characteristics of studies that evaluated sleep based on measures of motility.

Reference	N	Noise Source	Noise Metric	Outcome
Hong et al. (2006) [125]	12	Rail	L_{Amax} indoor	Exposure-response between probability of motility and indoor L_{Amax}. A higher probability of motility than in previous aircraft noise studies was found.
Frei et al. (2014) [84]	119	Road	L_{night}, 22:00–6:00, outdoor, most exposed facade	Decrease in sleep efficiency (percent) with outdoor L_{night}. Coefficients for random subject intercept linear regression: 30–40 dB: 0.20 (95% CI −1.21, 1.60), 40–55 dB: −0.85 (95% CI −2.42, 0.71), >55 dB: −4.06 (−6.78, −1.35)
Griefahn et al. (2000) [130]	377	Road and Rail	Indoor and outdoor whole night and individual event noise levels	No significant effect of noise on sleep parameters found.
Lercher et al. (2010) [126]	8	Rail	L_{Amax} indoor	Coefficient for L_{Amax}, in a linear regression for the probability of motility reaction was significant. (0.04, 95% CI 0.01–0.07, $p < 0.01$)
Ohrström et al. (2006) [128]	79	Road	$L_{Aeq,24hr}$ outdoor, most exposed facade	No significant effect of noise on sleep parameters was found.
Passchier-Vermeer et al. (2002) [64]	418	Aircraft	L_{Amax} indoor	Exposure-response relationship between motility and indoor L_{Amax}.
Passchier-Vermeer et al. (2007) [131]	262	Road and Rail	L_{Amax} indoor	Significant noise metric coefficient when comparing probability of motility reaction to an estimated indoor L_{Amax} level. Motility reaction was greater when there was higher levels of background noise.
Pirrera et al. (2014) [129]	45	Road	L_{Aeq} indoor	No significant difference in indoor average noise levels was found despite differences in outdoor noise level. No significant difference in time in bed, total sleep time, sleep latency, wake after sleep onset, or sleep efficiency was found.

7.3. Sleep Disturbance in Children

The results from sleep studies in children have suggested that they are less likely to awaken to noise events than adults, with a difference in sensitivity of approximately 10 dBA [132]. However, despite being less sensitive, children are still considered a vulnerable group due to their developmental state and also because of the difference in their sleep patterns. Children have earlier bedtimes and longer sleep durations than adults, which may overlap with periods of high traffic not accounted for by metrics such as L_{night}.

Five studies on the effects of road, rail, and aircraft noise on sleep in children published since 2000 were identified as part of this review (see Table 12). Ohrström et al. (2006) [128] conducted a study to examine the effect of road traffic noise on sleep in both adults and children. They conducted a main study which included a questionnaire and a more detailed study in which subjects filled out sleep logs and wore actigraphs for 4 days. The children in the study were between the ages of 9–12 years. In the main study a small yet significant decrease in self-reported sleep quality with increasing predicted outdoor $L_{Aeq,24hr}$ levels was found. However, no relationship between outdoor noise levels and actigraphy measured sleep parameters was found. Lercher et al. (2013) [133] found a small but significant relationship between road and rail noise (L_{den}) and a sleep disturbance index which was based on responses to questions on sleep onset, maintaining sleep, and tiredness in 3rd and 4th grade students. The variance explained by the models though was small. Ising and Ising (2002) [134] obtained self-reported measures of sleep for 56 children between the ages of 7–13. Noise levels were measured in the children's bedroom. They found that those children exposed to higher C-weighted maximum noise levels were more likely to report problems sleeping. Tiesler et al. (2013) [135] examined the relationship between predicted noise levels and self-reported sleep disturbance in children that were part of a population-based birth-cohort study called LISAplus. Data on sleep was available for 287 children and the mean age of children in the cohort studies was 10 years. They found a significant relationship between noise levels (L_{night}) at the least exposed façade and sleeping problems (OR 1.79, 95% CI 1.10–2.92) and difficulty falling asleep (OR 1.96, 95% CI 1.16–3.32) after controlling for a number of confounding variables including gender, age, and parental education. However, a significant relationship was not found for noise levels at the most exposed façade. They also found that those children reporting sleep problems were more likely to report emotional symptoms although this was not significantly related to noise level. Stansfeld et al. (2010) [136] examined whether self-reported sleep disturbance in children in the Munich study mediated the relationship between aircraft noise and cognitive performance. However, they did not find an effect.

Table 12. Characteristics of studies that evaluated sleep in children.

Reference	Age	*N*	Confounding Variables Adjusted for in the Statistical Analysis	Noise Source	Noise Metric	Outcome
Ising and Ising (2002) [134]	7–13 years	56	Age, gender, social status	Road	L_{Cmax} Indoors	Significant correlation between L_{Cmax} and awakenings during sleep and problems to fall asleep
Lercher et al. (2013) [133]	8–11 years	1251	Gender, health status, and mother's education	Road and Rail	L_{den} Outdoor most exposed facade	L_{den} was a significant predictor of self-reported sleep, but not when adjusted for sound perception score
Ohrström et al. (2006) [128]	Mean 10.9 years (range 9–12.9)	160 (survey) 79 (actigraphy)	None	Road	$L_{Aeq,24h}$ Outdoor most exposed facade	Decrease in self-reported mean sleep quality (0–10) < 55 dB: 8.6, 55–59 dB: 8.2, 60–64 dB: 8.2, >64 dB: 8.1. No association between actigraphy measured sleep parameters and noise level
Tiesler et al. (2013) [135]	10.1 ± 2.2 years	287	Gender, age, parental education level, mother's age at birth, television/computer usage, single parent status, sleeping alone, and orientation of the window	Road	L_{night} Outdoors, least exposed facade	Reporting any sleep problems: OR: 1.79 (95% CI 1.10–2.92) Reporting problems falling asleep: OR 1.96 (95% CI 1.16–3.32)

The results of four of the studies suggest that noise may lead to poorer self-reported sleep in children. Additional studies are needed though to determine the effect of noise on both subjective and objective measures of sleep in children. Also more studies are needed to examine whether nighttime noise exposure may contribute to attention deficits, emotional or behavioral problems, or reduced cognitive performance.

8. Summary of Available Evidence

A summary of the evidence for different noise sources and sleep outcome measures is shown in Table 13. For road, rail, and aircraft noise the focus of this review was to conduct a re-analysis for polysomnography measured awakenings and a meta-analysis for self-reported sleep outcome measures. The quality of the evidence that transportation noise causes cortical awakenings is moderate. The two studies reviewed were conducted using a similar methodology and exposure-response relationships were developed for all three transportation modes. The results from the analysis consistently indicate that a 10 dBA increase in the indoor maximum noise level is associated with an Odds Ratio for awakenings or sleep stage changes to Stage 1 of 1.3 or higher.

Table 13. Summary of findings.

Sleep Outcomes	Noise Source	Number of Participants (Studies)	Quality of Evidence	Noise Metric	Odds Ratio per 10 dBA Increase (95% CI)
Cortical Awakenings in Adults	Road	94 (2)	⊕⊕⊕O Moderate There was evidence of dose-response	Indoor $L_{AS,max}$	1.36 (1.19–1.55)
	Rail	33 (1)	⊕⊕⊕O Moderate There was evidence of dose-response	Indoor $L_{AS,max}$	1.35 (1.21–1.52)
	Aircraft	61 (1)	⊕⊕⊕O Moderate There was evidence of dose-response	Indoor $L_{AS,max}$	1.35 (1.22–1.50)
Self-Reported Sleep Disturbance in Adults (Noise Source Specified)	Road	20,120 (12)	⊕⊕⊕O Moderate There was evidence of dose-response	Outdoor L_{night}	2.13 (1.82–2.48)
	Rail	7133 (5)	⊕⊕⊕O Moderate There was evidence of dose-response	Outdoor L_{night}	3.06 (2.38–3.93)
	Aircraft	6371 (6)	⊕⊕⊕O Moderate There was evidence of dose-response	Outdoor L_{night}	1.94 (1.61–2.33)
Self-Reported Sleep Disturbance in Adults (Noise Source Not Specified)	Road	18,850 (4)	⊕OOO Very Low Confounding factors not accounted for in analysis, Imprecision low number of studies	Outdoor L_{night}	1.09 (0.94–1.27)
	Rail	8493 (3)	⊕OOO Very Low Confounding factors not accounted for in analysis, Imprecision low number of studies	Outdoor L_{night}	1.27 (0.89–1.81)
	Aircraft	3173 (3)	⊕OOO Very Low Confounding factors not accounted for in analysis, Imprecision low number of studies	Outdoor L_{night}	1.17 (0.54–2.53)
Motility Measures of Sleep in Adults	Road, Rail, Aircraft	1320 (8)	⊕⊕OO Low Single event analysis indicates dose-response	L_{Amax} and L_{Aeq}	Not estimated
Self-Report and Motility Measured Sleep Disturbance in Children	Road, Rail, Aircraft	1754 (4)	⊕OOO Very Low Inconsistency in results, small number of studies	Varied across studies	Not estimated
Self-Reported Sleep Disturbance in Adults	Wind Turbine Noise	3971 (6)	⊕OOO Very Low Inconsistency in results and imprecision due to small sample sizes at highest noise levels	Outdoor A-weighted SPL	1.60 (0.86–2.94)
All Sleep Outcome Measures	Hospital Noise	964 Adults/67 Children (13 Adults/4 Children)	⊕OOO Very Low Inconsistency in results and imprecision due to small sample sizes	Varied across studies	Not estimated

For self-reported sleep outcome measures, the quality of the evidence is dependent on the wording of the questions. When individuals were asked whether road, rail, or aircraft noise affected sleep a significant increase in the odds of being highly sleep disturbed was found for a 10 dBA increase in outdoor L_{night} levels for all sources. However no significant increase was found when the noise source was not mentioned. Because the dose-response relationships between Lnight and percentage highly sleep disturbed were statistically significant and showed Odds Ratios > 2, for both road and rail noise, we upgraded our GRADE assessment from very low to moderate quality for studies using questions that did mention noise as the cause (see Table 13, and Tables S3 and S4). However, we downgraded to very low quality for studies using the respondents' answers to questions that did not mention the noise source, due to inadequate adjustment for confounding and imprecision due to the low number of studies. This suggests that for self-reported measures it is annoyance or attitude to the nighttime noise that may be driving the increase of reported sleep disturbance outcomes with L_{night} level. However, whether or not the question is reflective of sleep disturbance or attitude to nighttime noise both are important endpoints. For the other outcome measures and noise sources, we were not able to derive pooled odds ratios.

9. Conclusions

This review demonstrates effects of traffic noise on objectively measured sleep physiology and on subjectively assessed sleep disturbance (including sleep quality, problems falling asleep, and awakenings during the night). The evidence for other sources of noise (e.g., hospital noise, wind turbine noise) is conflicting or only emerging and did not allow for the derivation of exposure-response functions. There is biologic plausibility that chronic night time exposure to relevant levels of noise can contribute to negative health consequences like cardiovascular disease. Although recent epidemiological studies have shown stronger relationships of nocturnal noise exposure [34] with negative health consequences compared to daytime noise exposure, studies directly investigating the link between acute noise-induced sleep disturbance and long-term health consequences are missing and not an easy undertaking. However, disturbed sleep has immediate next-day consequences (e.g., increased sleepiness, impaired cognitive performance) that may increase the risk for errors and accidents, and thus sleep deserves protection from noise even in the absence of a direct link to long-term health consequences. The exposure-response functions provided in this report can be used to assess the degree of noise-induced sleep disturbance. It is plausible that preventing acute effects of noise on sleep will likely also prevent long-term negative health consequences.

Supplementary Materials: The following are available online at http://www.mdpi.com/1660-4601/15/3/519/s1, Table S1: Characteristics and outcomes of studies not included in the meta-analysis for self-reported sleep outcomes, Table S2: GRADE Table for the quality of evidence of noise from road, rail, and aircraft noise and cortical awakenings in adults, Table S3: GRADE Table for the quality of evidence of noise from road, rail, and aircraft noise and self-reported sleep disturbance in adults (noise source specified), Table S4: GRADE Table for the quality of evidence of noise from road, rail, and aircraft noise and self-reported sleep disturbance in adults (noise source not specified), Table S5: GRADE Table for the quality of evidence of noise from road, rail, and aircraft noise and motility measures of sleep in adults, Table S6: GRADE Table for the quality of evidence of noise from road, rail, and aircraft noise and self-report and motility measured sleep disturbance in children, Table S7: GRADE Table for the quality of evidence of noise from wind turbines associated with effects on sleep, Table S8: GRADE Table for the quality of evidence of noise from hospitals associated with effects on sleep, Table S9: Model coefficients for the random study effect logistic regression model (Mixed) and the GEE model for the percent Highly Sleep Disturbed due to Aircraft noise, Table S10: Model coefficients for the random study effect logistic regression model (Mixed) and the GEE model for the percent Highly Sleep Disturbed due to Road noise, Table S11: Model coefficients for the random study effect logistic regression model (Mixed) and the GEE model for the percent Highly Sleep Disturbed due to Train noise, Table S12: Model coefficients for the random subject effect logistic regression model (Mixed) and the GEE model for the probability of a sleep stage change to wake or S1 for Aircraft noise, Table S13: Model coefficients for the random subject effect logistic regression model (Mixed) and the GEE model for the probability of a sleep stage change to wake or S1 for Road noise, Table S14: Model coefficients for the random subject effect logistic regression model (Mixed) and the GEE model for the probability of a sleep stage change to wake or S1 for Train noise. Table S15: Percent Highly Sleep Disturbed for road, rail, and aircraft noise for the logistic regression models shown in Figure 8. Figure S1: Percent Highly Sleep Disturbed. Random study effect logistic regression (gray) and GEE regression (black) with 95% confidence intervals (dashed lines); Figure S2: Probability of a sleep stage change to wake or S1. Random subject effect logistic regression (gray) and GEE regression (black) with 95% confidence intervals (dashed lines); Table S16: Criteria used to rate the bias of individual studies; Table S17: Bias ratings for studies on noise from road, rail, and aircraft noise and cortical awakenings in adults; Table S18: Bias ratings for studies on road, rail, and aircraft noise and self-report sleep disturbance; Table S19: Bias ratings for studies on wind turbine noise; Table S20: Bias ratings for studies on hospital noise and sleep in adults; Table S21: Bias ratings for studies on hospital noise and sleep in children; Table S22: Bias ratings for studies on hospital noise studies that had interventions; Table S23: Bias ratings for studies on noise from road, rail, and aircraft noise and cardiac and blood pressure outcomes; Table S24: Bias ratings for studies on noise from road, rail, and aircraft noise and actigraphy outcomes; Table S25: Bias ratings for studies on noise from road, rail, and aircraft noise and children's sleep; Table S26: Bias ratings for studies that were not included in the meta-analysis of self-reported sleep outcomes for road, rail, and aircraft noise.

Acknowledgments: This systematic review has been funded by the World Health Organization Regional Office for Europe supported by Swiss Federal Office for the Environment, and delivered as part of the evidence-base that underpins the Environmental Noise Guidelines for the European Region. All rights in the work, including ownership of the original work and copyright thereof is vested in WHO and the authors of the manuscript. The authors alone are responsible for the views expressed in this publication and they do not necessarily represent the decisions or the stated policy of the World Health Organization. We would also like to thank Mark Brink, Thu Lan Nguyen, Dirk Schreckenberg, Abigail Bristow, Takashi Yano, Jiyoung Hong, Jaana Halonen, Gordana Ristovska, Martin Röösli, Lex Brown, Gunn Marit Aasvang and Theo Bodin, who graciously shared de-identified self-reported sleep data from their studies. We would also like to thank Uwe Müller and Daniel Aeschbach (both German Aerospace Center) for sharing the polysomnography data.

Author Contributions: M.B. and S.M. completed the analysis and drafted the manuscript.

Conflicts of Interest: M.B. is the current president of the International Commission on Biological Effects of Noise (ICBEN).

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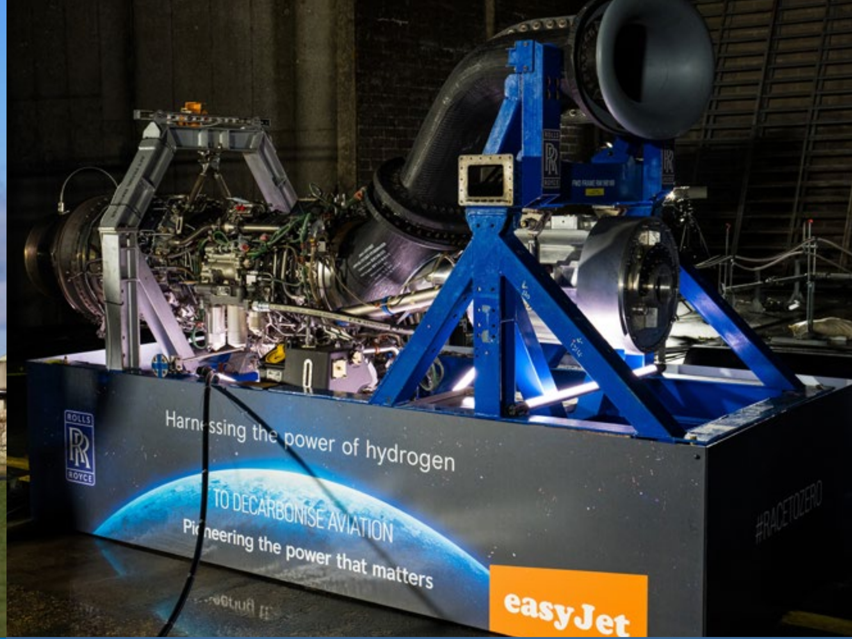
APPENDIX C: JET ZERO STRATEGY: ONE YEAR ON (JULY 2023)



Department for Transport

Jet Zero Strategy

One Year On

Department for Transport
Great Minster House
33 Horseferry Road
London SW1P 4DR

We are committed to decarbonising aviation and delivering Jet Zero

Last year we published our world-leading Jet Zero Strategy setting out the government's approach to achieving net zero 2050 (or "Jet Zero") for UK aviation. The Strategy focuses on the rapid development of technologies in a way that maintains the benefits of air travel, whilst maximising the opportunities that decarbonisation brings for the UK.

Since then, we've made significant progress in the delivery of our commitments, most notably:

- UK leadership helped secure a ground-breaking new goal for international aviation of net zero by 2050, sending a vitally important policy signal to the global market.
- We have published our second SAF mandate consultation and are delivering a further round of the Advanced Fuels Fund, crucial milestones towards achieving our aim for the UK to be a world leader in the development, production, and use of SAF.
- And most recently, the government response was published to the "Developing the UK Emissions Trading Scheme" consultation, with a range of new commitments for aviation, including a net zero consistent cap and aviation free allocation phase-out by 2026.

However, we know there is still so much more to do. Achieving Jet Zero is hugely challenging, and we need all parts of the sector to play their part. Through our well-established partnerships such as the Jet Zero Council, we must continue to deliver, and ensure we use the Jet Zero transition to unlock the benefits of green aviation technology for the UK.

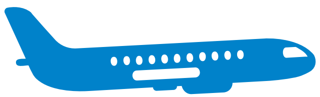
[redacted]

Baroness Vere of Norbiton
Minister for Aviation, Maritime and Security

Executive Summary

It is critical that the aviation sector plays its part in delivering the UK's net zero commitment and the government is already supporting a variety of technology, fuel and market-based measures to address aviation emissions.

The One Year On highlights our key successes in the past year across the three guiding principles and six core policy measures, outlining our next steps to achieve Jet Zero and the challenges we must overcome to get there.



The government remains committed to achieving Jet Zero, whilst being flexible over the pathway to achieve it. We continue to be guided by our three strategic principles of: **international leadership, delivered in partnership and maximising opportunities**; and our six core policy measures of: **system efficiencies, sustainable aviation fuels (SAF), zero emission flight (ZEF), markets and removals, influencing consumers**, and **addressing non-CO_2**.

International leadership is crucial given the interconnected global nature of the sector. Last year, the UK played a leading role in influencing adoption by the International Civil Aviation Organization (ICAO) of a new global goal for international aviation of net zero CO_2 emissions by 2050. We are now working towards the ICAO 3rd Conference on Aviation Alternative Fuels (CAAF/3) in November, where we want to agree a global target and framework for SAF.

Government cannot deliver Jet Zero alone, which is why over the past year we have continued to **deliver in partnership** with industry, academia and NGOs, including through the Jet Zero Council which has published Two-Year Plans for the work of the Council's SAF and ZEF Delivery Groups.

In transitioning to Jet Zero, we also need to make sure we **maximise opportunities** to grow new industries and technologies, and by protecting and creating jobs across the entire sector and UK.

We are focusing our efforts on unlocking the potential of a UK SAF industry and growing the UK's aerospace sector through continued R&D support to develop more efficient and zero emission aircraft through the Aerospace Technology Institute (ATI) programme.

We have also made significant progress across our six core policy measures.

Improving **system efficiencies** of our existing airspace, aircraft and airports remains a key foundation of our approach. In the last year, we published a Call for Evidence on our 2040 Zero Emission English Airports target, co-invested in the development of new ultra-efficient emission aircraft technology through the ATI programme and provided over £9m of financial support to the UK's Airspace Modernisation programme.

Sustainable aviation fuel (SAF) is crucial to our efforts to decarbonise, and we want the UK to be a global leader in its development, production and use. Some key successes this year include launching the £165m Advanced Fuels Fund to support the development of commercial scale SAF plants within the UK, publishing the second SAF mandate consultation, and publishing Phillip New's report on 'developing a UK SAF industry' alongside a government response, all as part of our efforts to support investment in UK SAF production.

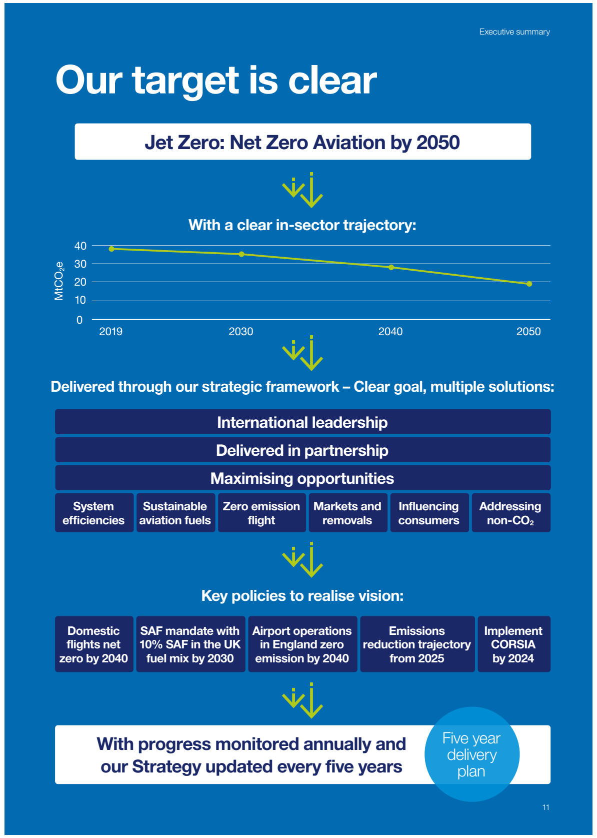
We also continue to see significant potential for **zero emission flight (ZEF)** in decarbonising the sector. We continued to co-invest in new zero-carbon emission aircraft technology through the ATI programme, and supported research into airport preparedness for handling hydrogen aircraft through £4.2m of funding to the Zero Emission Flight Infrastructure (ZEFI) Project.

We continue to consider that **carbon markets and removals** are essential levers for reaching Jet Zero. Some highlights from the past year include negotiating to uphold the environmental integrity of ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), publishing the government response to the Developing the UK Emissions Trading Scheme consultation, and supporting the development of greenhouse gas removals technologies.

Influencing consumers is a further important strand of our approach; we want to preserve the ability for people to fly, whilst supporting consumers to make sustainable aviation choices. We have worked closely with the Civil Aviation Authority (CAA) to publish a Call for Evidence on what environmental information should be provided to consumers when they are looking for and booking flights.

Addressing non-CO_2 impacts of aviation remains challenging, given significant scientific uncertainty regarding the magnitude of their effects on the climate, though we have made progress in the last year. We have developed a programme of research to advance our understanding of aviation's non-CO_2 impact and identify mitigation options, and established a Non-CO_2 Task and Finish group as part of the Jet Zero Council.

Whilst our Jet Zero goal is clear, we recognise that **big challenges** remain. Reaching our goal relies on emerging technologies with varying degrees of uncertainty around their commercialisation and deployment; the production of SAF and hydrogen will rely on significant supplies of feedstock and green electricity, and we must make progress internationally to achieve emissions reductions from international aviation without competitive disadvantage for the UK, or carbon leakage. We will continue to work closely with industry, academia, NGOs, other states and across government to address these challenges as we deliver Jet Zero.



Key successes a year on from the Jet Zero Strategy

October

ICAO adopts net zero 2050 CO_2 emissions goal for international aviation

The UK played a leading role in the technical work and negotiations over the last four years leading to the International Civil Aviation Organization (ICAO) adopting a new global goal for international aviation of net zero CO_2 emissions by 2050, at its 41st Assembly in October 2022. This places the sector on a trajectory firmly aligned with the Paris Agreement's 1.5°C global temperature target. It provides clear and collective policy direction, will help draw investment in technology and infrastructure, and creates a platform for developing further specific international measures through ICAO.

January

ZeroAvia reaches key milestone for zero emission flight

In January, ZeroAvia conducted a successful test flight of a 19-seater Dornier 228 twin-engine aircraft using hydrogen fuel cell propulsion– a key milestone in the transition to zero emission commercial aviation. The flight was conducted as part of the HyFlyer II project, a research programme backed by the UK government to develop a zero-emission powertrain for 9–19 seat commuter aircraft. ZeroAvia is targeting bringing the aircraft into commercial service by 2025.

February

Launch of the 2040 Zero Emission Airport Target Call for Evidence

In February, we held the seventh Jet Zero Council meeting where we launched the 2040 Zero Emission Airport Target Call for Evidence. The Call for Evidence, covering airports in England, will enable us to address the challenges raised by industry, such as residual emissions which may result from specific equipment, as well as better understand any support needed to achieve this target. We also announced £113 million of co-investment in hydrogen and battery electric flight technologies through the ATI programme.

Key successes a year on from the Jet Zero Strategy

March

Significant progress on SAF

In March, we delivered a significant package of announcements on SAF including: publication of the second SAF mandate consultation, outlining the proposed detailed design of a scheme that will seek to generate demand for SAF, provide an incentive to SAF producers and deliver carbon savings; launching a further round of the Advanced Fuels Fund, making a further £55.8m available to support UK SAF projects through to construction; and announcing the University of Sheffield as the delivery partner for the UK SAF Clearing House.

April

Jet Zero Council publishes Two-Year Plan

In April, we held the eighth Jet Zero Council meeting where we published the government response to Philip New's report on 'Developing a UK SAF industry', which sets out how the government is already taking action to address some of the report's recommendations, and what more could be done to secure meaningful investment in UK SAF production. In addition, the Council published its Two-Year Plan showing the action needed in the coming years to support the delivery of Jet Zero by 2050.

July

Government response to the UK ETS consultation

In July, we published the government response to the Developing the UK ETS consultation, setting out a range of commitments including a tighter emissions cap and the future of aviation free allocation. These commitments are intended to support a cost-effective approach to the aviation sector achieving net zero by 2050.

Part 1

Our 2050 trajectory

Rolls Royce easyJet hydrogen test engine.
Image courtesy of Rolls Royce.

Our UK net zero commitment

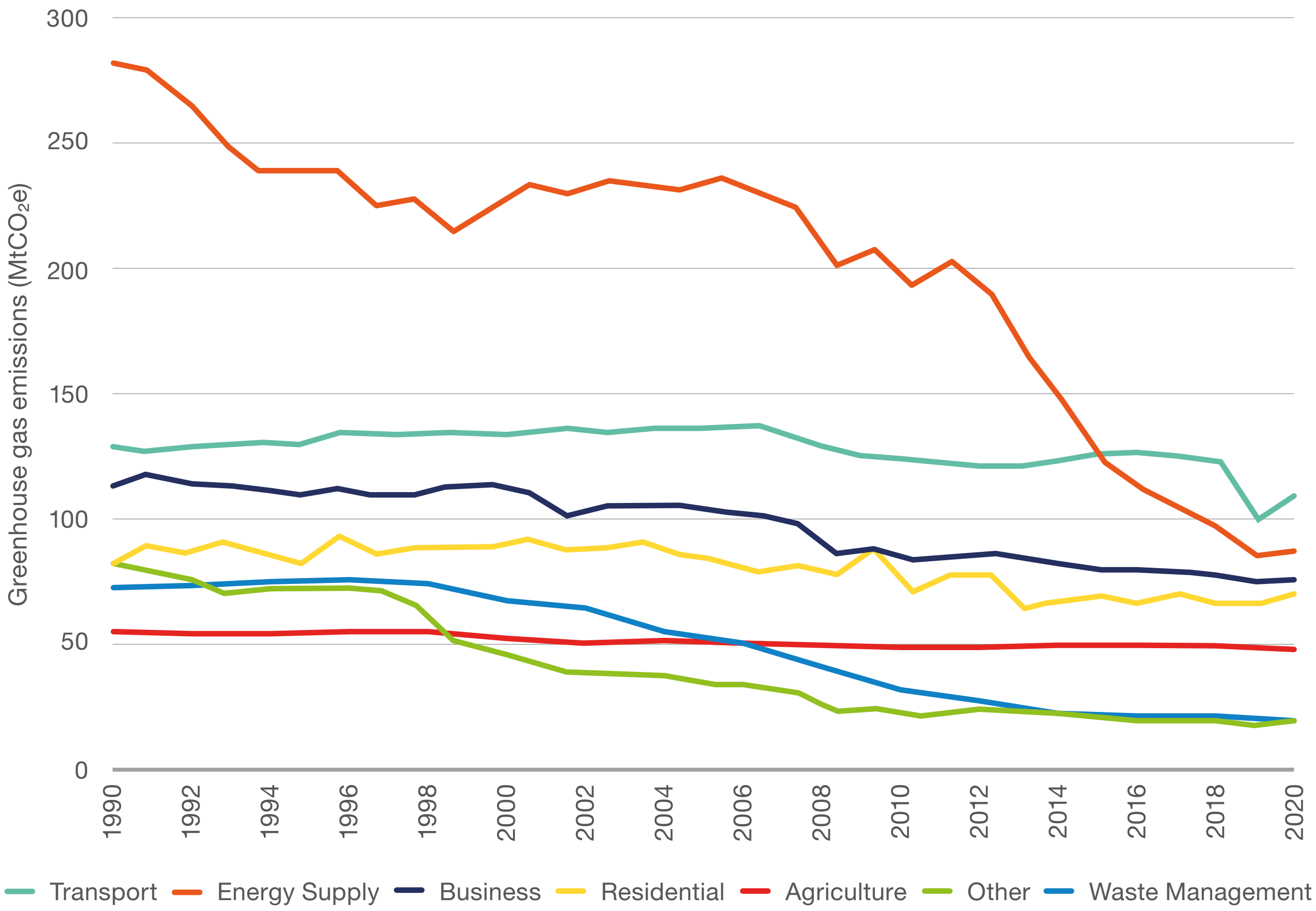
The government has continued to take major steps in driving the delivery of our net zero commitments across the whole UK economy, simultaneously providing new opportunities to grow the economy and support hundreds of thousands of green, high skilled jobs.

The UK has already made huge progress in decarbonising its economy and decoupling emissions from economic growth. Between 1990 and 2021, UK territorial emissions were cut by 48%, whilst the economy grew by 65%.

Over the past year the government has further set out the UK's approach to net zero and energy security, responding to the expert recommendations made in the *Independent Review of Net Zero.* The *Net Zero Growth Plan* – published as part of the wider *Powering Up Britain Plan* – sets out the actions the government will take to ensure the UK remains a leader in the net zero transition. The *Carbon Budget Delivery Plan* clearly lays out the policies and proposals that will enable us to meet carbon budgets.

It is in this context that aviation decarbonisation must take place, as we continue to transition to a sustainable future in which we maintain the benefits of air travel.

Territorial UK greenhouse gas emissions by National Communication (NC) sectors, 1990-2021 ($MtCO_2e$)



Source: Final UK greenhouse gas emissions national statistics 1990-2021 Excel data tables. **Note:** Other includes Public, Industrial Processes and the Land Use, Land Use Change and Forestry (LULUCF) sectors. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1134664/greenhouse-gas-emissions-statistical-release-2021.pdf.

Our CO_2 emissions reduction trajectory

Transport remains the largest emitting sector in the UK, and by 2035, aviation is expected to be one of the largest emitting transport modes.

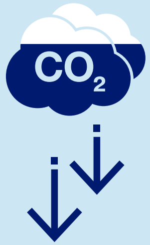
To generate momentum for reducing emissions in one of the most challenging sectors to decarbonise, we set a CO_2 emissions reduction trajectory in the Jet Zero Strategy. This sees UK aviation emissions peak in 2019, with interim targets of 35.4 $MtCO_2e$ in 2030, 28.4 $MtCO_2e$ in 2040, and 19.3 $MtCO_2e$ in 2050.

The latest data from the Department for Energy Security and Net Zero greenhouse gas emissions statistics shows that **UK aviation activity and emissions remain below 2019 levels** due to the impact of the COVID-19 pandemic but are likely to continue to increase in the short-term as the sector recovers, making efforts to rapidly decarbonise vitally important.

In 2021, UK aviation greenhouse gas emissions were 14.0 $MtCO_2e$ (13.3 $MtCO_2e$ from international aviation and 0.7 $MtCO_2e$ from domestic aviation) – 63% below 2019 levels, and a further **9% reduction on 2020 emissions**.

Provisional estimates for 2022 UK international aviation greenhouse gas emissions show that, as the sector began to recover throughout 2022, UK international aviation emissions increased to 26.0 $MtCO_2e$ – a 95% increase on 2021 international aviation emissions, but **still 29% below 2019 levels**.

In-sector interim targets



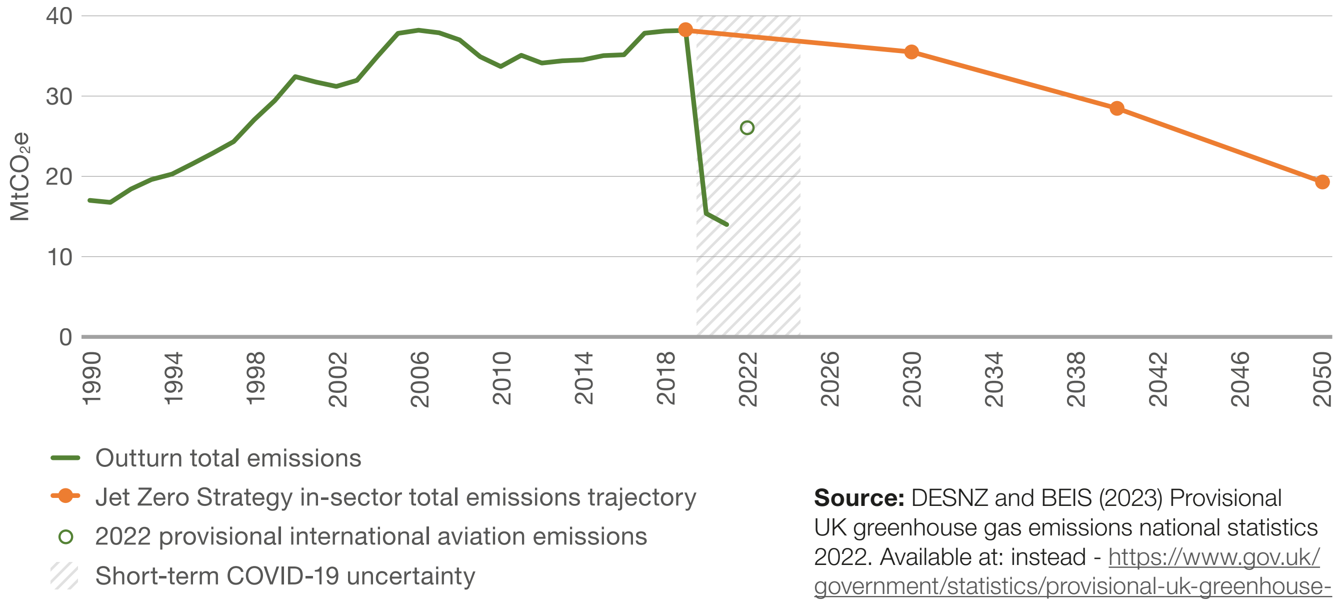
38.2 $MtCO_2e$ in 2019

35.4 $MtCO_2e$ in 2030

28.4 $MtCO_2e$ in 2040

19.3 $MtCO_2e$ in 2050

UK aviation emissions



Source: DESNZ and BEIS (2023) Provisional UK greenhouse gas emissions national statistics 2022. Available at: instead - https://www.gov.uk/government/statistics/provisional-uk-greenhouse-gas-emissions-national-statistics-2022.

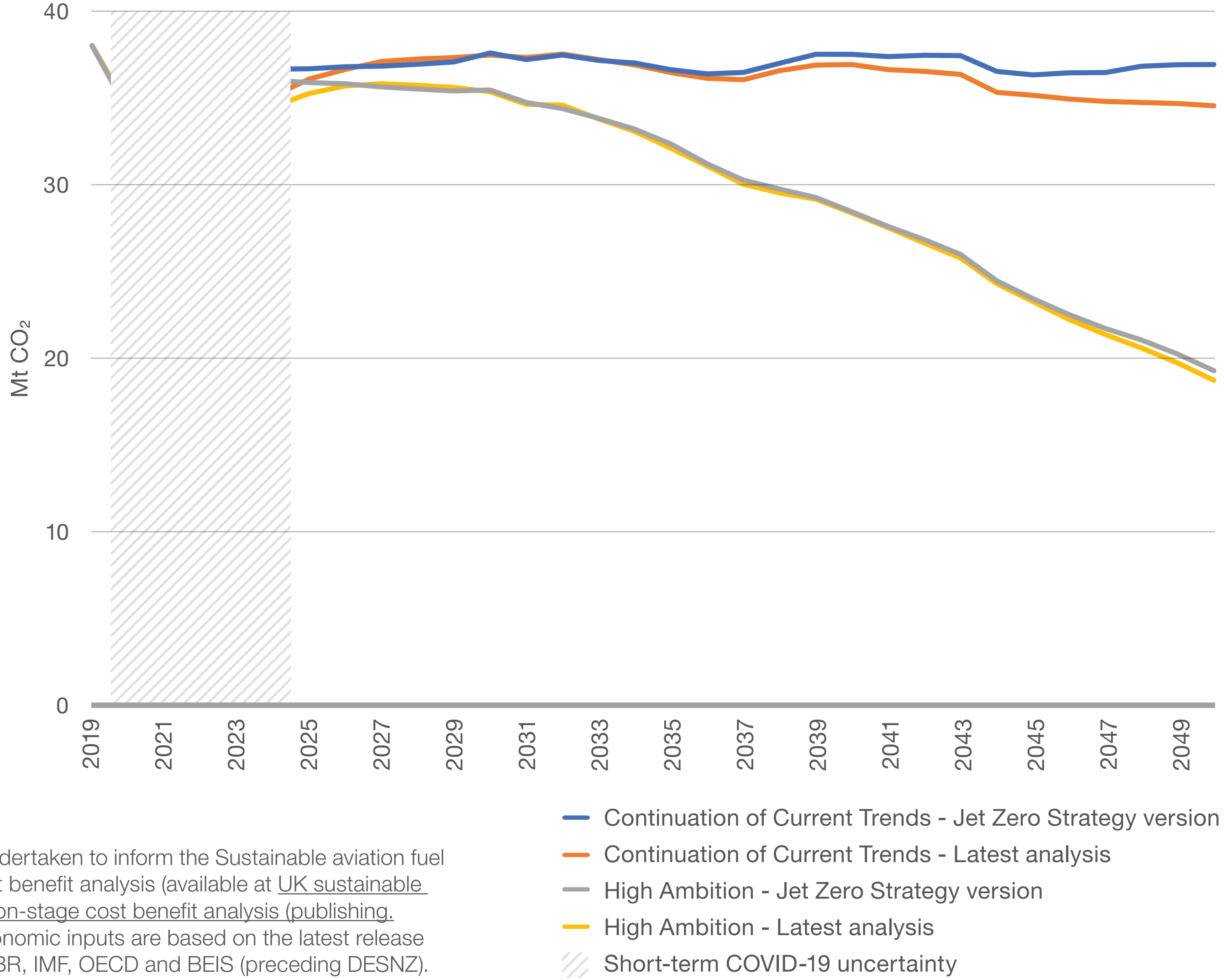
Our Jet Zero Strategy modelling

Our CO_2 emissions reduction trajectory is based on our Jet Zero Strategy High Ambition scenario, which sees a combination of fuel efficiency improvements, zero-emission aircraft, SAF and carbon markets reduce UK aviation emissions by 63% by 2050, with 37% of emissions to be abated outside of the aviation sector using greenhouse gas removal technologies.

This year, we have updated our scenarios to reflect the latest macroeconomic conditions, including updating inputs on oil prices, GDP and consumption growth, and foreign exchange rates. This has had the impact of reducing forecast passenger demand growth under our High Ambition scenario to 52% in 2050, relative to 2018 levels, compared to 70% in the published Jet Zero Strategy.

The updated High Ambition scenario has **18.7 $MtCO_2e$ residual emissions in 2050** compared to 19.3 $MtCO_2e$ in the original analysis. We will continue to keep our modelling under review in light of the latest data and new evidence as it emerges.

Updated Jet Zero Strategy analysis



Source: Internal DfT analysis undertaken to inform the Sustainable aviation fuel mandate consultation-stage cost benefit analysis (available at UK sustainable aviation fuel mandate: consultation-stage cost benefit analysis (publishing.service.gov.uk)). These macroeconomic inputs are based on the latest release as of March 2023, from ONS, OBR, IMF, OECD and BEIS (preceding DESNZ).

Monitoring and reviewing our progress to Jet Zero

We are committed to a data led approach in our policy making and we remain transparent in our modelling towards Jet Zero. We have also committed to reviewing progress against our CO_2 emissions reduction trajectory on an annual basis from 2025, once the sector has recovered from the short-term impacts of COVID-19.

In order to respond quickly to emerging trends and ensure transparency of information, through the Jet Zero Strategy we committed to publishing more timely aviation emissions data from 2023. In March, the government's annual provisional UK greenhouse gas emissions statistics for 2022 included estimates of international aviation emissions for the first time, reducing the time lag for official statistics on international aviation emissions by nearly a year.

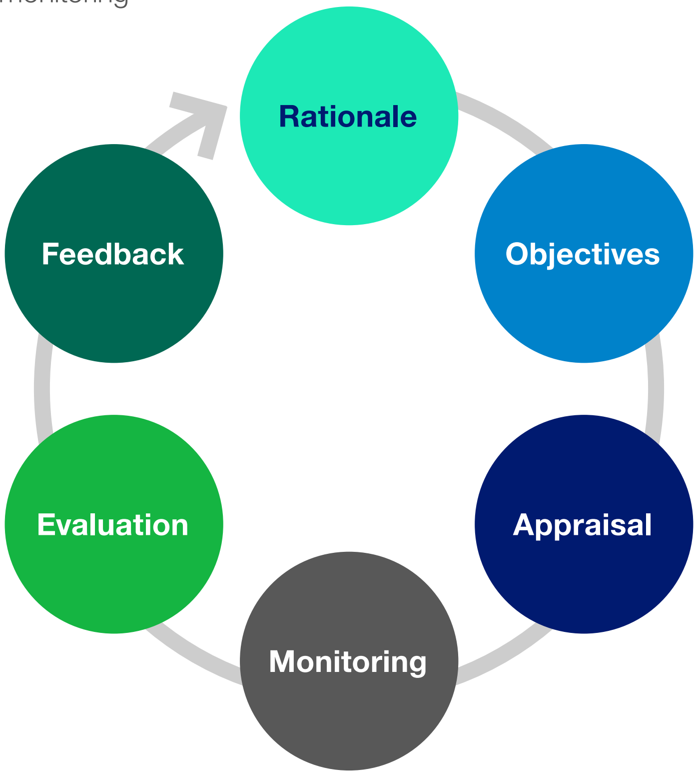
To further increase transparency, by December this year we plan to publish an explanation of available aviation emissions data and a comparison of different methodologies, alongside the CAA's UK Aviation Environmental report. This will include a short user engagement survey to better understand the public need for aviation emissions statistics and to inform future statistical development.

We will use this exercise to continue to explore the most appropriate methodology to monitor aviation emissions and use this to monitor the sector's progress against our emissions reduction trajectory.

We have committed to reviewing our Jet Zero Strategy every five years, with the first review in 2027. As part of this, we will review our overall strategic approach and associated Jet Zero scenarios.

To further our monitoring and to effectively track progress against our Jet Zero targets, we plan to produce a comprehensive monitoring and evaluation framework which will include suggestions for appropriate data collection methods, monitoring metrics, and evaluation activities.

As the Jet Zero Strategy contains a range of strategic principles and policy measures this adds complexity to evaluating the strategy and means we must sufficiently plan and prioritise monitoring and evaluation activity to develop a suitable approach. This framework will outline our future evaluation workplan, which will also feed into the five-year reviews of the Jet Zero Strategy.



Part 2

Progress against our strategic framework

ZeroAvia flight using hydrogen fuel cell propulsion.
Image courtesy of ZeroAvia.

A clear goal, with multiple solutions

The government remains committed to achieving net zero aviation by 2050, whilst being flexible over the pathway to achieve it. We continue to use our strategic framework – a clear goal, with multiple solutions – to deliver on Jet Zero.

This publication reflects on progress across the three principles and six core policy measures set out in the Jet Zero Strategy.

We recognise that a range of technologies are likely to be required in parallel to reach net zero aviation in 2050. We have set out expectations of progress including mandating the use of at least 10% SAF in the UK jet fuel mix by 2030 and completion of the Airspace Modernisation programme by 2040.

Within our strategic framework we have also set an earlier target for UK domestic aviation to reach net zero by 2040. We know there are a range of opportunities for achieving the target, including across the technology pillars of SAF, zero emission flight and greenhouse gas removals. In due course we will launch a call for evidence on achievement of the target.

Jet Zero Strategy Principles

International leadership

Given the interconnected global nature of the sector, international action is critical to achieving our Jet Zero ambitions. Through the International Civil Aviation Organization (ICAO) we are influencing global ambition and action on aviation decarbonisation.

Last year ICAO adopted a new global goal for international aviation of net zero CO_2 emissions by 2050, after several years of technical work and negotiations, in which the UK played a leading role. This places the sector on a trajectory firmly aligned with the Paris Agreement's 1.5ºC global temperature target.

It provides clear and collective policy direction, will help draw investment in technology and infrastructure, and creates a platform for developing further specific international measures through ICAO. We are now working towards the ICAO 3rd Conference on Aviation Alternative Fuels (CAAF/3) in November, where we are aiming to secure a quantified target for the uptake of SAF that reflects its key role in meeting net zero by 2050.

Additionally, the International Aviation Climate Ambition Coalition, launched by the UK at COP26, provides a forum for coordination and collaboration between likeminded states. Its membership has now grown to 60 states from all world regions. The Coalition played an important role in securing the ICAO net zero by 2050 agreement, and we will continue to convene the Coalition and work to deliver our shared ambitions, for CAAF/3 and beyond.

We are also drawing on UK expertise to support other states tackle their emissions, as part of our commitment to the ICAO principle of 'No Country Left Behind'. The UK launched a pilot project in partnership with Kenya to assist states in East Africa in implementing CORSIA effectively. We are also one of the first participants in the ICAO Assistance, Capacity Building, and Training for Sustainable Aviation Fuels (ACT-SAF) programme and we will continue to play a leading role by expanding our CORSIA and SAF capacity building programmes to additional states in 2023.

Alok Sharma ICAO. Image courtesy of DfT

Delivered in partnership

All parts of the sector must continue to work together to develop, test, implement and invest in the solutions needed to decarbonise aviation.

In the past year we have continued to strengthen the work of the Jet Zero Council, our key forum for partnership working between industry, government and academia. The council brings together senior leaders in aviation and aerospace to drive the delivery of new technologies and innovative ways to cut aviation emissions. The Council is now chaired by the Secretaries of State for Transport, Business and Trade, and Energy Security and Net Zero recognising the vital roles that all these sectors – aviation, aerospace and energy – will need to play in the Jet Zero transition.

The Council has met twice already in 2023, and the Council's Delivery Groups (focused on SAF and zero emission flight) have published their Two-Year Plan setting out the actions required to support Jet Zero by 2050. The Council has hosted four Jet Zero webinars to engage the wider community through our Jet Zero Council Associate Membership, showcasing the work of the Council and taking a deeper dive into the SAF mandate, aviation's non-CO_2 impact and airspace modernisation. Further webinars will take place this year, and the Council will meet again in the autumn.

In addition to the Jet Zero Council, we continue to work through other partnerships including the Aerospace Growth Partnership and the Aviation Council which is leading on Airspace Modernisation.

We are also working with the Airspace Change Organising Group (ACOG) and have now received draft Iteration 3 of their Masterplan (Scottish cluster), the coordinated implementation plan for airspace changes in the UK up to 2040. This is currently being reviewed by stakeholders and will be put out for public consultation over the summer prior to publication in the autumn.

Jet Zero Council 8. Image courtesy of DfT

Delivered in partnership case study

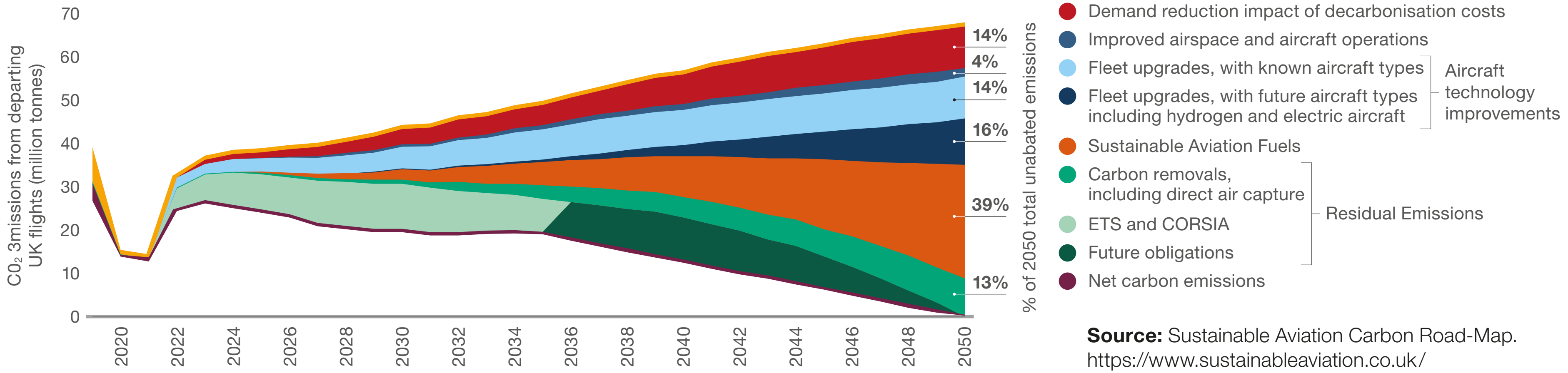
Sustainable Aviation Carbon Road-Map

In April, Sustainable Aviation, a coalition of UK airlines, airports, aerospace manufacturers, air navigation service providers, SAF producers and other key business partners, published their updated decarbonisation road-map. The updated road-map confirms that UK aviation can continue to grow whilst meeting its commitment to net zero carbon emissions by 2050, reflecting advances in sustainable aviation technology already delivered in the UK which will accelerate the industry's transition to net zero around the world.

The road-map forecasts UK aviation emissions to reach around 67 $MtCO_2e$ by 2050, without any intervention. Their modelling suggests around 40% of these emissions could be removed using SAF, 33% by operational and fleet efficiency improvements, including moving to zero emission aircraft, 14% by reduced demand due to the additional costs of decarbonisation measures, and the remaining 13% of residual emissions by greenhouse gas removals (GGRs) outside of the aviation sector.

These measures are in line with those considered in our Jet Zero Strategy. Unsurprisingly, given the complexity of decarbonising the aviation sector and high levels of uncertainty, the contributions of individual measures do not align exactly with those implied by our modelling. Under the Jet Zero Strategy High Ambition scenario, 17% of the required emission reductions in 2050 come from SAF. 15% from fuel efficiency improvements, 4% from zero carbon aircraft, 27% from ETS and CORSIA and 37% from abatement outside the sector. We will continue to work with industry to identify the challenges and barriers we need to work together to overcome.

Sustainable Aviation Carbon Road-Map: A path to Net Zero



Source: Sustainable Aviation Carbon Road-Map. https://www.sustainableaviation.co.uk/

Delivered in partnership case study

MOD's Defence Aviation Net Zero Strategy

This summer the Ministry of Defence published their Defence Aviation Net Zero Strategy.

Emissions from military flying are not currently included in our Jet Zero Strategy or emissions reduction trajectory, however the new MOD strategy will bring defence in line with the Jet Zero Strategy approach and will lead the military activity necessary for the UK's Defence Aviation Sector to contribute to net zero by 2050, in line with wider Defence aspiration.

Defence is committed to playing its full part in the government's goal to reach net zero. The previous Chief of the Air Staff has also outlined his ambition for the RAF to act as a Defence leader in this area and become the first net zero air force by the year 2040. This provides an excellent opportunity for collaboration across government as we develop the new technologies required for Jet Zero.

Sustainable aviation fuel on voyager trail. Image courtesy of MOD

Delivered in partnership case study

General Aviation

The General Aviation sector is well placed to encourage the early adoption of innovative zero emission aircraft. In the last year we have commissioned and published independent research which provides an evidence baseline of the carbon emissions emitted by General Aviation activities, including a range of policy options for consideration.

The research concluded that General Aviation activity in the UK (in 2019) emitted approximately 800,000 tonnes of CO_2e (in comparison to 38.2 million tonnes of CO_2e emitted by the total aviation sector). Business aviation flights are responsible for approximately 75% of this total. The research also considered a number of high-level solutions that could help General Aviation achieve net zero by 2050. These include zero carbon aircraft, zero emissions ground vehicles, smart heating, lighting and energy management, smart runways and both on-site and off-site renewable energy generation.

We are working with the CAA, following their work with Open Innovation, to further develop policy options for providing support to the General Aviation sector to assist them in reducing their environmental impact, including the potential for unleaded and SAF.

This will also include ensuring the General Aviation sector are kept apprised of policy developments on our work to decarbonise the commercial aviation sector.

General Aviation light aircraft that can be used as a test bed for new technologies. Image courtesy of Flickr account GH@BHD

Maximising opportunities

The transition to Jet Zero presents unique opportunities to grow new industries and technologies, and protect and create jobs across the entire sector and UK.

Alongside the Jet Zero Strategy we published the Jet Zero Investment Flightpath showcasing the UK's leading role in the development and commercialisation of new, low and zero emission aviation technologies, and the associated investment opportunities.

We continue to focus on the economic benefits of the Jet Zero transition. By 2030, a UK SAF industry could contribute £1.8bn in Gross Value Added (GVA), including upstream activities. This could increase to £10.1bn by 2050. Domestic production of SAF could also support 10,350 jobs by 2030 across the supply chain, rising to 60,000 in 2050.

For zero emission flight, there are notable UK economic opportunities in relation to the design and manufacture of such aircraft or parts, as well as the expertise in rolling out zero emission flight infrastructure. The ATI's Flyzero project estimated that zero emission aircraft could constitute 50% of the global fleet by 2050 requiring 29,200 aircraft deliveries worth between $1.9 to $2.1tn.

We will continue to work with industry, investors and across government through the Jet Zero Council and other forums to ensure we maximise these opportunities and work together to address barriers to investment.

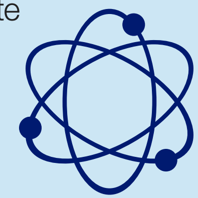
To ensure we have the right future aviation skills in place, we have commissioned independent research by Connected Places Catapult to determine what skills the workforce will need in order to fully integrate into all emerging aviation technologies, including decarbonisation. We will continue to explore what additional, aviation-focused research on future skills could be of value in supporting the industry's transition to Jet Zero.

The ATI's Flyzero project estimated that **zero emission aircraft** could constitute

50%

of the global fleet

by 2050



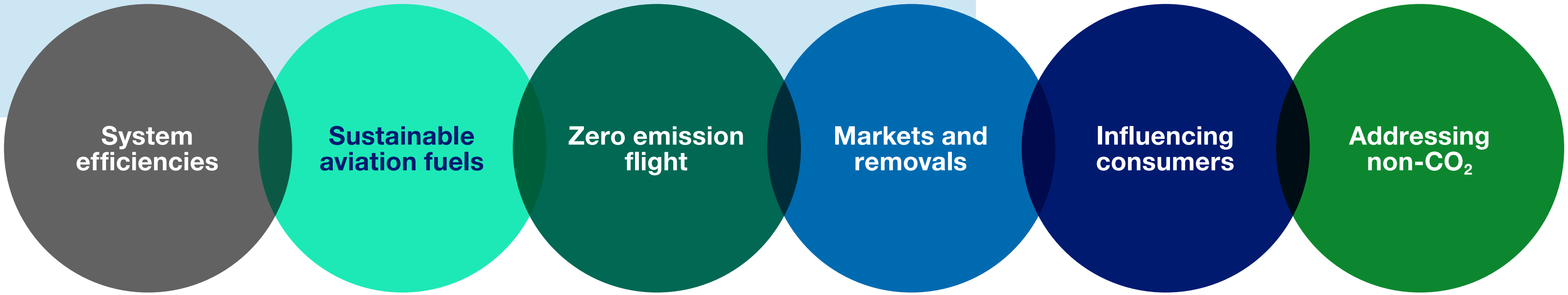
By 2030, a UK SAF industry could contribute **£1.8bn** in **Gross Value Added** (GVA), including upstream activities.

This could increase to **£10.1bn by 2050.**

Domestic production of SAF could also support 10,350 jobs by 2030 across the supply chain, rising to **60,000 in 2050**

Note: Forecasts are based on independent analysis conducted by ICF consulting firm for the Sustainable Aviation Net Zero Carbon Road-Map 2023. The jobs and GVA figures are based on direct, construction and upstream jobs benefits. Analysis assumes UK SAF production costs are equivalent to wider global SAF production costs.

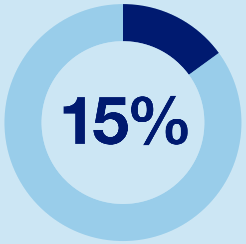
Jet Zero Strategy Policy measures



System efficiencies

Continuing to realise efficiencies from our airspace, aircraft and airports remains a key lever in decarbonising the sector in the near term.

Under our Jet Zero Strategy High Ambition scenario, **system efficiencies deliver 15% of the reduction in UK aviation emissions** required to meet Jet Zero



In the past year, we have…

- Published a Call for Evidence on our 2040 Zero Emission Airport target which seeks views on the scope and design of achieving zero emissions at airports in England.
- Industry and government have co-invested £105m in the development of new ultra-efficient aircraft technology, such as high aspect ratio wings and lightweight composite structures, through the ATI programme. These technologies could be applied to improve the energy efficiency of future SAF or zero-carbon emission aircraft. We also co-invested £147m in cross-cutting and enabling technologies, such as digital design and optimising material utilisation, that underpin both ultra-efficient and zero-carbon aircraft opportunities.
- Agreed and provided UK expertise for a new workstream within the ICAO Committee on Aviation Environmental Protection to update the stringency of the international standard for aeroplane CO_2 emissions by 2025.
- Provided over £9m of financial support to the Airspace Modernisation programme as part of the government's continued commitment to both supporting recovery in the aviation sector post-pandemic, and to our net zero decarbonisation aims.
- Worked with the CAA to publish the refreshed Airspace Modernisation Strategy, extending the Strategy to 2040 and reaffirming our commitment to delivering this key infrastructure programme.
- Worked with NATS who have implemented Free Route Airspace above Wales and South West England, saving 12,000+ tonnes of CO_2/year and 150,000 nautical miles of flying, which is the equivalent of seven trips around the world.

Next, we plan to…

- Publish an independent research project later this year, to understand the commercial feasibility of adopting zero carbon technologies required to reach zero emissions airport operations by 2040. This report will provide further evidence on the viability of the 2040 target and give an increased understanding of the requirements, timeliness and costs of infrastructure adaption.
- Analyse responses to the Call for Evidence on the Zero Emission Airport Operations Target, publish a summary of responses, and the government response and publish a consultation early next year, setting out our proposals for implementing the target.
- Continue to support the development of ultra-efficient manufacturing processes and technologies through the ATI programme.
- Implement Free Route Airspace across the North of England in autumn 2025, and over London and the South East in autumn 2026.

System efficiencies case study

Rolls-Royce tests on the new UltraFan engine

The Rolls-Royce UltraFan demonstrator aeroengine – the largest in the world – proves a suite of new technologies that deliver greater fuel efficiency and can be scaled to suit both narrow and wide body markets.

Its greater efficiency and sustainability is achieved through a combination of new engine and core architecture, composite fan technology, lean burn combustor, and power gearbox. UltraFan can be 25% more efficient than the first-generation Trent and offers 40% less NOx, 35% less noise and almost zero non-volatile particulates at cruise.

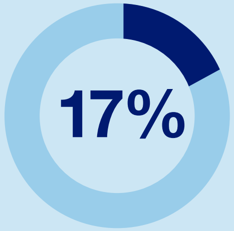
UltraFan is designed to be future-proof, ready to run on 100% SAF from day one and with scope to develop into hybrid-electric and hydrogen variants. The cutting edge technologies in UltraFan reduce fuel burn and therefore the cost of flying whatever the fuel mix in the future; SAF, hydrogen, hybrid-electric and traditional jet fuel. Many of these technologies can be retrofitted into Trent engines to increase efficiency and reduce the environmental impact of today's engines too.

Importantly, development of the UltraFan has been accelerated through partnership between Rolls-Royce and the UK government via the ATI programme. This partnership draws on and strengthens the UK's world-leading aerospace R&D ecosystem, including universities, industry partners, SMEs, and research centres, and grows the next generation of skills the UK needs to deliver the energy transition in aviation and beyond.

Rolls Royce UltraFan in the final build stage.
Image courtesy of Rolls Royce

Sustainable Aviation Fuel

Our vision is for the UK to be a global leader in the development, production and use of SAF, helping us to achieve Jet Zero.



Under our Jet Zero Strategy High Ambition scenario **the uptake of Sustainable Aviation Fuel delivers 17% of the reduction in UK aviation emissions** required to meet Jet Zero

In the past year, we have...

- Launched the £165m Advanced Fuels Fund to support the development of commercial scale SAF plants within the UK. Five projects have already been awarded a share of £82.5m and we are now considering applications for the second round of funding. This competition drives our ambition to see at least five commercial-scale SAF plants under construction in the UK by 2025. Once operational, the five projects alone will produce over 300,000 tonnes of SAF each year and create thousands of green jobs across the UK.
- Announced Virgin Atlantic as the winner of up to £1m of government grant funding to run the world's first transatlantic flight on 100% SAF, from London to New York.
- Published the second SAF mandate consultation, outlining the proposed detailed design of a scheme that will seek to generate demand for SAF, provide a financial incentive / price support to SAF producers and deliver carbon savings.
- Appointed the University of Sheffield as the delivery partner for the UK SAF Clearing House, supported by Ricardo, to accelerate the testing and approval of new SAF.
- Commissioned and published Phillip New's report on 'developing a UK SAF industry' alongside a government response which sets out how we are already taking action to address some of the report's recommendations, and what more could be done to secure meaningful investment in UK SAF production.

Next, we plan to...

- In Summer 2023, launch the UK SAF Clearing House to begin supporting the testing and approval of innovative new fuels. We will also announce the winners of the second application round of the Advanced Fuels Fund.
- Further progress the consideration of options for additional revenue certainty for a UK SAF industry. This would need to be provided via an industry funded intervention and if required, we will launch a formal government consultation later this summer.
- Negotiate to secure strong outcomes from the ICAO 3rd Conference on Aviation Alternative Fuels (CAAF/3) in November, including a quantified target for the global uptake of SAF that reflects its key role in meeting net zero by 2050, and a robust framework to support states with its development and deployment.
- By the end of 2023, publish the government response to the second SAF mandate consultation and support Virgin Atlantic to successfully operate the world's first transatlantic flight on 100% SAF, from London to New York.
- Build on the success of the *Clean Skies for Tomorrow* SAF Ambassadors Group by utilising the group to further support our international SAF ambitions.
- In 2025, bring the SAF mandate into force and complete the funding period for projects supported by the Advanced Fuels Fund.

SAF case study

Investment wins

In December 2022, the first round of the £165m Advanced Fuels Fund awarded a share of £82.5m to five projects:

alfanar Energy Ltd (Lighthouse Green Fuels, Teesside)

Developing a commercial scale plant that uses gasification and Fischer-Tropsch technology to convert black bin bag waste into SAF. The plant is expected to be operational in 2028 and produce 86.6 kt/y of SAF when at full operational capacity.

Fulcrum BioEnergy Ltd (NorthPoint, Ellesmere Port)

Developing a commercial scale plant that uses gasification and Fischer-Tropsch technology to convert black bin bag waste into SAF. The plant is expected to be operational in 2027 and produce 83.7kt/y of SAF when at full operational capacity.

LanzaTech UK Ltd (DRAGON, Port Talbot)

Developing a commercial scale plant that converts industrial off-gases into ethanol and then uses alcohol-to-jet technology to produce SAF. The plant is expected to be operational in 2026 and produce 79kt/y of SAF when at full operational capacity.

Velocys Plc (Altalto, Immingham)

Developing a commercial scale plant that uses gasification and Fischer-Tropsch technology to convert black bin bag waste into SAF. The plant is expected to be operational in 2028 and produce 37.4kt/y of SAF when at full operational capacity.

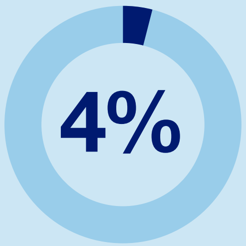
Velocys Plc (e-Alto, location tbc)

Developing a large demonstration plant that uses power-to-liquid technology to convert carbon dioxide from a fossil gas-powered electricity plant and hydrogen made from renewable electricity into SAF.

Baroness Vere at Alfanar's Teesside project. Image courtesy of Alfanar

Zero Emission Flight

Zero Emission Flight is a technically challenging endeavour however the last year has seen a number of exciting developments.



Under our Jet Zero Strategy High Ambition scenario **Zero Emission Flight delivers 4% of the reduction in UK aviation emissions** required to meet Jet Zero

In the past year, we have…

- Co-invested £119 million with industry in the development of new zero-carbon emission aircraft technology, such as high-end batteries and liquid hydrogen combustion jet engines, through the ATI programme. We also co-invested £147m in cross-cutting and enabling technologies, such as digital design and optimising material utilisation, that underpin both ultra-efficient and zero-carbon aircraft opportunities.
- Seen Rolls-Royce and easyJet undertake a ground demonstration of a hydrogen powered gas turbine. With with support from government: Rolls-Royce launched projects to develop a liquid hydrogen combustion jet engine; in January ZeroAvia initiated flight testing of a Dornier 228 aircraft using a hydrogen-electric engine and Cranfield Aerospace Solutions are preparing to commence a programme to flight test their hydrogen-electric aircraft in early 2024.
- Supported research into airport preparedness for handling hydrogen aircraft through £4.2m of funding to the Zero Emission Flight Infrastructure (ZEFI) Project. The findings from the projects second year were published by Connected Places Catapult in March 2023, setting out operational changes and infrastructure requirements needed for different airport archetypes to successfully adopt hydrogen powered flight.
- Building on the recommendations of the FlyZero project, government is now funding the initial phase of a Hydrogen Capability Network. Led by the ATI, the Phase 0 project aims to define the operating model for a group of open-access facilities designed to accelerate the development of liquid-hydrogen aircraft technologies and capabilities.

Next, we plan to…

- Continue to co-invest in new zero-carbon aircraft technology development projects through the ATI programme.
- Support the CAA through £939,150 of funding from the Government's Regulatory Pioneers Fund to initiate a Hydrogen Regulatory Challenge to enhance the understanding of hydrogen-related risks to aviation safety.
- Take forward work in the Jet Zero Council's Zero Emission Flight Delivery Group's recently published Two Year Plan.
- This summer, announce projects successful in the Tees Valley Transport Hydrogen Hub competition. Following a successful phase one, the Hub's phase two is co-locating supply (hydrogen fuel and refuelling infrastructure) and demand (vehicles). The Hub is already creating significant levels of industry interest, with BP and Protium Green Solutions announcing their intentions to build large scale green hydrogen production in the area.

Zero emission flight case study

Project NAPKIN

The New Aviation Propulsion Knowledge and Innovation Network (NAPKIN), a coalition of manufacturers, airports and universities, published a report in November 2022 on the potential for hydrogen as a fuel for zero emission flight, with a focus on modelling the introduction of zero emission aircraft into regional and short-haul aviation within the UK. Part of Innovate UK's Future Flight Challenge – a five-year programme with £300m of joint government and industry funding – the report took a whole systems approach to understand the UK Zero Emission Flight challenge, covering technology challenges, market conditions and infrastructure requirements. The report's findings support the feasibility of the Jet Zero Strategy's ambition to have zero emission flight in the UK by 2030 and net zero UK domestic aviation by 2040 target. The findings of the project may be found on the Heathrow Airport Limited website here:

NAPKIN | Heathrow

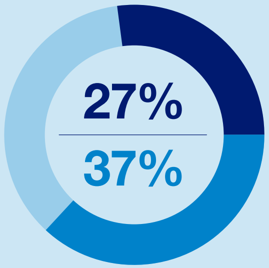
Hydrogen plane by Cranfield Aerospace Solution partnered in Project NAPKIN. Image provided by Cranfield Aerospace Solution

Markets and removals

The UK remains a leader in the establishment and development of carbon markets and views carbon pricing and greenhouse gas removals (GGRs) as essential levers for reaching net zero. They play an important role for aviation given the challenge of zero emission technology.

Under our Jet Zero Strategy High Ambition scenario, **the impact of carbon pricing delivers 27% of the reduction in UK aviation emissions** required to meet Jet Zero

Greenhouse Gas Removals will address the residual 37% emissions outside the aviation sector



In the past year, we have…

- Negotiated to uphold the environmental integrity of ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) at its first Periodic Review, with offsetting expected to begin from 2024.
- Introduced legislation setting out a near-term approach to the offsetting requirements of CORSIA in the UK.
- Published the government response to the Developing the UK Emissions Trading Scheme consultation, which includes a tighter overall emissions cap and aviation free allocation phase-out by 2026.
- Confirmed that we believe the UK ETS is an appropriate long-term market for GGRs, subject to robust monitoring, reporting and verification and the management of wider impacts.
- Expanded the scope of the UK ETS to include flights from Great Britain to Switzerland.
- Confirmed that the government intends to develop a GGR business model to support a portfolio of UK GGR projects to deploy this decade, based on a 'contracts for difference' structure, subject to value for money considerations.
- Announced in the Net Zero Growth Plan that government is minded to enable engineered GGR projects to apply for both Track-1 Expansion (ie mid-2020s) - and Track-2 (ie by 2030) of the Carbon Capture, Usage and Storage Programme subject to criteria under development.
- Launched a pilot project in partnership with Kenya under the ICAO capacity building programme to assist East African states in implementing CORSIA.

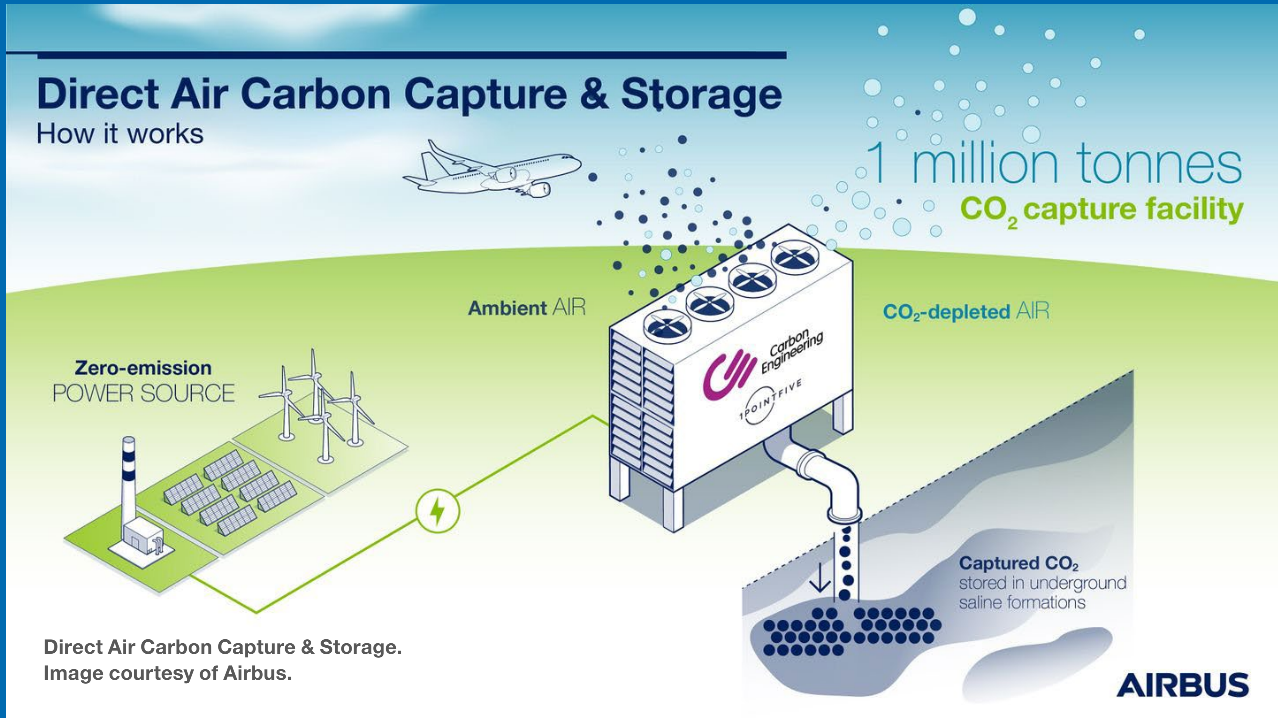
Next, we plan to…

- Continue to support CORSIA and begin moving to strengthen the scheme, working through ICAO's next Periodic Review (to be concluded in 2025).
- Publish a second consultation on CORSIA, including interaction with the UK ETS, seeking to have all legislation to implement CORSIA in place by 2024.
- Develop proposals for consultation through the UK ETS Authority on how the UK ETS should treat the use of SAF by aircraft operators in future.
- Aim to carry out a further consultation in 2023 on the inclusion of engineered and nature-based GGRs in the UK ETS, through the UK ETS Authority. This will address market design and eligibility requirements alongside other relevant considerations.
- Consider further how the UK ETS should cover aviation's non-CO_2 climate impacts.

Markets and removals case study

Airbus and Direct Air Carbon Capture and Storage

Airbus and a number of major airlines – including easyJet, International Airlines Group, and Virgin Atlantic – signed Letters of Intent last July to explore opportunities for a future supply of carbon removal credits from direct air carbon capture technology. Direct Air Carbon Capture and Storage (DACCS) is a high-potential technology that involves filtering and removing CO_2 emissions directly from the air using high powered fans. Once removed from the air, the CO_2 is safely and permanently stored in geologic reservoirs. As the aviation industry cannot capture CO_2 emissions released into the atmosphere at source, a direct air carbon capture and storage solution would allow the sector to extract the equivalent amount of emissions from its operations directly from atmospheric air. As part of the agreements, the airlines have committed to engage in negotiations on the possible pre-purchase of verified and durable carbon removal credits starting in 2025 through to 2028.



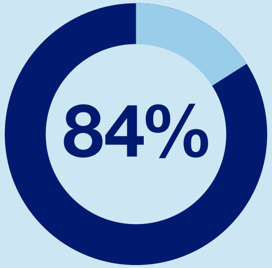
Direct Air Carbon Capture & Storage.
Image courtesy of Airbus.

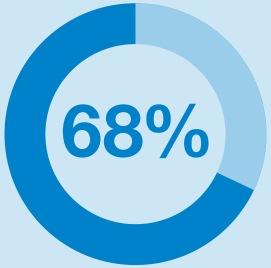
Influencing consumers

We are clear that we want to preserve the ability for people to fly whilst supporting consumers to make sustainable aviation choices.

Our public attitudes tracker shows that **84% of people are concerned about climate change**,

and up to **68% of respondents would be willing to pay more** for flights using greener alternatives.





In the past year, we have…

- Worked with the CAA in publishing their Call for Evidence on what environmental information should be provided to consumers when they are looking for and booking flights. The Call for Evidence closed in April and we are currently analysing response.
- Undertaken a cross-sector literature review on eco-labelling to understand what factors influence consumer behaviours.
- Asked car users to indicate whether they travelled to airports in an electric car through the CAA's Departing Passenger Survey recognising the government's wider ambitions to increase the use of electric cars. In time this will allow government and airports to track the % of electric vehicle use by passengers over time and help monitor progress in improving surface access.

Next, we plan to…

- Work with the CAA to publish a consultation on environmental information provision setting out our proposed approach and methodology for implementation.
- Through our engagement with airports, we will continue to encourage them to work with airlines, local authorities and local transport providers to consider how they can develop integrated service offerings with surface transport providers. Our expectations are that airports, through their surface access strategies, set targets for sustainable passenger and staff travel to the airport which meet where possible the ambitions set by government and for these to be monitored by their respective Airport Transport Forums. Improvements to surface access to airports are generally funded by the airports themselves.

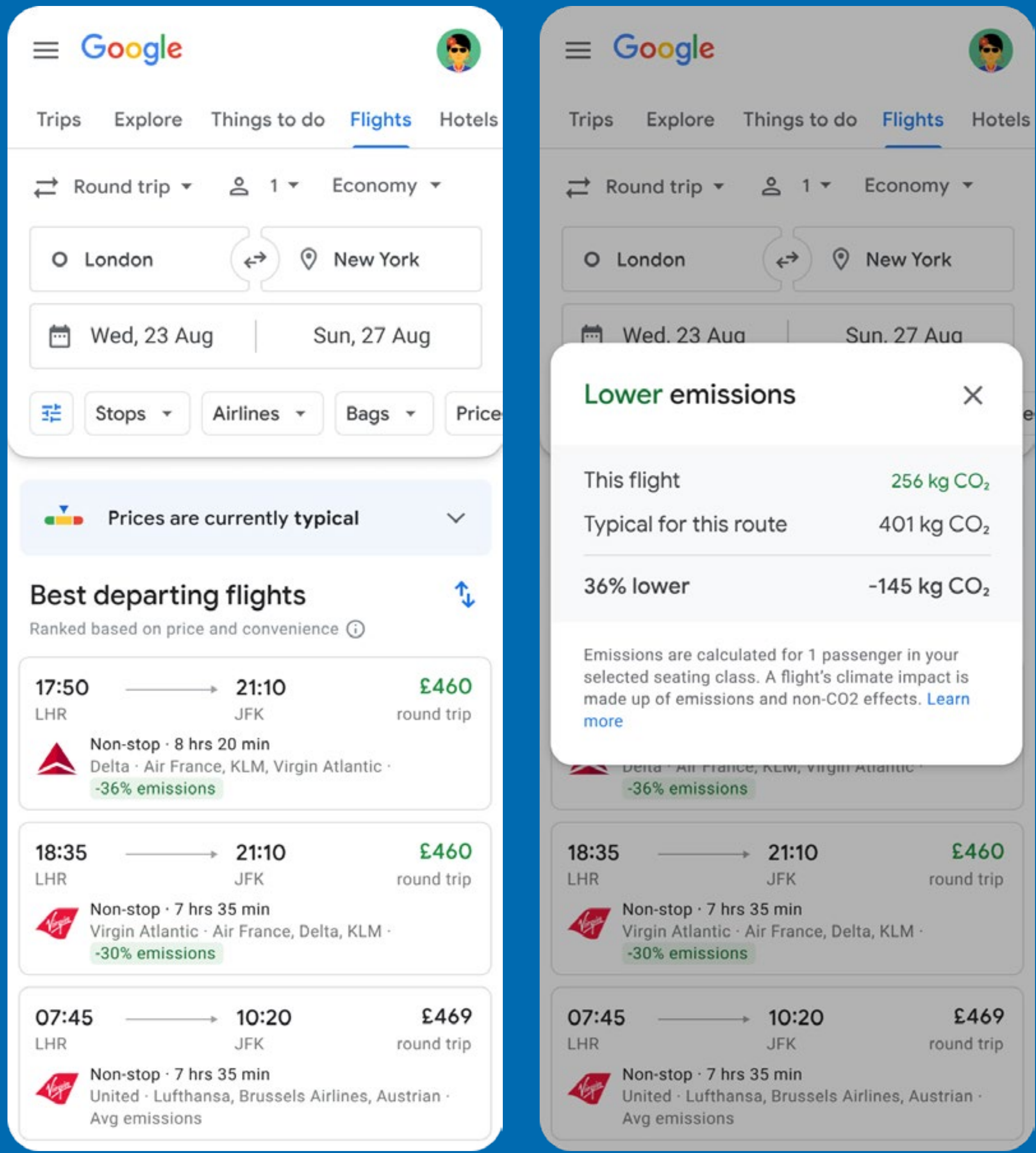
Influencing consumers case study

Google's Travel Impact Model

Google has been displaying flight emissions information to travellers alongside the price and duration of the flight since 2021. When users are choosing among flights of similar cost or timing, they can also factor carbon emissions into their decision to make an informed choice. Google's internal research shows that consumers find it helpful to be presented with clear, accurate, consistent, transparent and easy-to-understand information about kg/CO_2 of their flight options.

It's critical that travellers can find a single, rigorous answer about their air travel emissions footprint no matter where they want to research or book their trip. Therefore, in 2022, Google made the methodology used on Google Flights publicly available as the Travel Impact Model (TIM). The Travel Impact Model is a public and freely-accessible methodology for predicting the per-passenger CO_2 emissions produced by an upcoming flight. The model combines flight's origin and destination, aircraft type, cabin class, seat configuration, load factors and average aircraft utilisation to estimate CO_2 emissions per flight and per passenger. Today, the Travel Impact Model powers emissions estimates on Google Flights, as well as other leading travel sites through Google's work in the Travalyst coalition.

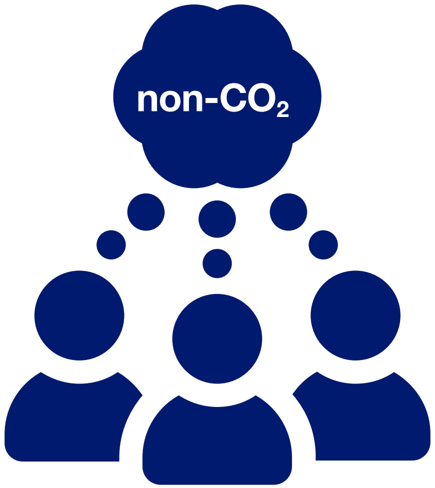
For any inquiries please contact:
[redacted]



Google's Travel Impact Model.
Images courtesy of Google.

Addressing non-CO_2

Whilst the impact of CO_2 emissions are well understood and can be quantified, academic research shows that there continues to be significant uncertainty regarding the magnitude of aviation's non-CO_2 impacts on the climate.



In the past year, we have…

- Launched Expressions of Interest (EOIs) for two DfT-funded research projects. The first of these projects will support a literature review of existing research on aviation's non-CO_2 impacts and evaluate methodologies for measuring aviation's non-CO_2 impacts, with a view to shaping further research and mitigation options. The second project will investigate the impact of reducing the aromatic content of kerosene on contrail formation.
- Worked closely with academics, industry, and the Natural Environmental Research Council (NERC) to scope out a multi-year research programme to further develop our understanding of aviation's non-CO_2 impact and identify mitigation options.
- Established a Non-CO_2 Task and Finish group as part of the Jet Zero Council. The first meeting took place in June. The group will be supporting the government's non-CO_2 research programme and also looking to collectively accelerate the work on addressing aviation's non-CO_2 impact.
- Continued to fund scientific research into aviation's non-CO_2 climate effects through our contract with Manchester Metropolitan University. An important recent publication that in part used HMG funding "A greenhouse gas balance for aviation in line with the Paris Agreement".
- Responded to calls for evidence on the development of the UK Emissions Trading Scheme (UK ETS), including exploring whether and how aviation's non-CO_2 climate impact could be included in the UK ETS.

Next, we plan to…

- Further develop the multi-year non-CO_2 research programme in collaboration with NERC and initiate the research projects. The projects will seek to improve our understanding of aviation's non-CO_2 impact as there continues to be significant uncertainty regarding the magnitude of these impacts. Through this project we will also seek to identify, better understand, and develop potential options for addressing aviation's non-CO_2 impact such as using SAF, hydrogen, and contrail avoidance technology.
- Undertake further work on how non-CO_2 impacts could be monitored and included in the UK ETS, in line with our aim to price aviation's non-CO_2 climate impact once scientific understanding and consensus permit.

Addressing non-CO_2 case study

Airbus non-CO_2 projects

Airbus is actively working on a large portfolio of projects focused on improving the scientific understanding of non-CO_2 emissions, reducing uncertainties and creating strategies and operating procedures to reduce their climate impact. They are also evaluating and developing solutions which include SAF and Hydrogen fuels, improvements to engines, and optimising flight operations. Current work streams include measuring emissions and their impacts on contrail formation using different types of engine technologies and fuels including through the use of 100% SAF.

In preparation for operational scenarios for contrail avoidance, Airbus is leading a SESAR project CICONIA. This explores the hypothesis that re-routing aircraft around the worst-case ice supersaturated regions at high altitude will minimise the generation of the most warming contrails. CICONIA aims at providing a complete picture of the operational non-CO_2 mitigation strategies and their associated real impact on climate (including balance with CO_2), economics and operations. Real time simulation and flight trials will be used, testing new air traffic management concepts.

To complement this project, Airbus will continue to work further with partners to investigate enhanced weather forecast solutions, including potential for integration of additional weather data sources, to formulate requirements for consideration.

Airbus A350 flight testing with 100% SAF, with a DLR chase aircraft to directly measure Non-CO_2 emissions

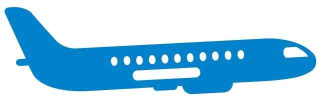
Part 3

Conclusion & summary of next steps

RAF voyager completing an air-to-air refueling with SAF.
Image courtesy of RAF.

We have made great strides over the last year, but big challenges remain

We need to continue to work across the aviation sector, and with experts across the economy to ensure we continue to make progress on our path to decarbonise aviation.



Technological readiness

SAF, zero-carbon emission aircraft and Greenhouse Gas Removals (GGRs) are emerging technologies with varying degrees of uncertainty around the timeline for bringing into service. We are continuing to work closely with industry, including through the Jet Zero Council and the Aerospace Growth Partnership, to drive forward their development at pace for use in the aviation sector.

International ambition

International ambition is essential to achieving emissions reductions from international aviation without competitive disadvantage for the UK, and to avoid carbon leakage. We are continuing to work with other states through ICAO and beyond, with a focus on implementation of the new net zero 2050 global goal.

Revenue uncertainty

A SAF mandate will give a clear signal to investors of the vital role government believes this technology will play in the UK while also providing a level of price support. We do, however, recognise that the long-term revenue certainty of UK production facilities remains a concern for investors and the aviation sector. That is why we have committed in our response to Philip New's report to consider industry funded options to increase future revenue certainty of UK SAF plants, working in partnership with the sector.

Energy and feedstock demand

We recognise there is uncertainty around SAF feedstock availability and continue to work closely with colleagues across government to ensure that the most up-to-date evidence and modelling is reflected throughout the policy design of the SAF mandate. In addition the direct use of hydrogen in aviation (either through its combustion or in a fuel cell) is dependent upon the production of low carbon hydrogen with implications for electricity demand.

Summary of next steps

Summer 2023

Launch the UK SAF Clearing House

Announce the winners of the second application round of the Advanced Fuels Fund

Further progress the consideration of revenue certainty options for supporting the development of a UK SAF industry. If required, following further engagement, we will launch a formal government consultation this summer

Autumn 2023

Ninth meeting of the Jet Zero Council

October 2023

Respond to the CCC's 2023 progress report aviation recommendations

November 2023

Negotiate to secure strong outcomes from the ICAO 3rd Conference on Aviation Alternative Fuels (CAAF/3)

By the end of 2023

Publish the government response to the second SAF mandate consultation

Support Virgin Atlantic to successfully operate the world's first transatlantic flight on 100% SAF, from London to New York

Publish a second consultation on implementing CORSIA in the UK, including its interaction with the UK ETS

Analyse responses to the Zero Emission Airport operations Target Call for Evidence and publish the government response

Work with the CAA to consult on environmental information provision

Launch a Call for Evidence on our target for domestic aviation to reach net zero by 2040

2024

Consult on our proposals for implementing the Zero Emission Airport operations Target

All legislation to implement CORSIA in place

2025

First review of progress against our emissions reduction trajectory

Implement Free Route Airspace across the North of England

At least five commercial-scale UK SAF plants under construction

UK SAF mandate introduced

2026

Implement Free Route Airspace over London and the South East

Phaseout of aviation UK ETS free allowances

2027

First review of the overall strategic approach set out in the Jet Zero Strategy

Key milestones on our pathway to Jet Zero beyond 2027

2030

In-sector interim target of 35.4MtCO_2e

Zero emission routes connecting different parts of the UK

At least 10% SAF in UK aviation fuel mix

10GW of UK low carbon hydrogen production

2032

5 year strategy review

2035

First large zero emission commercial aircraft expected to enter into service

2037

5 year strategy review

2040

All UK domestic aviation net zero

All airport operations in England zero emission

In-sector interim target of 28.4MtCO_2e

2042

5 year strategy review

2047

5 year strategy review

2050

Net zero aviation in-sector interim target of 19.3MtCO_2e

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Internal DfT analysis undertaken to inform the Sustainable aviation fuel mandate consultation-stage cost benefit analysis (available at UK sustainable aviation fuel mandate: consultation-stage cost benefit analysis (publishing.service.gov.uk)).

This updated modelling has fed into recent government publications, including the Carbon Budget Delivery Plan, and the second SAF mandate consultation.

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Flights from Great Britain to Switzerland have been included in the UK ETS since the start of 2023. Flights from Northern Ireland to Switzerland will be included when the Northern Ireland Assembly is able to progress legislation.

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Department for Transport