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# Assessing System Safety Risks in LH2-Powered Aircraft Ground Operations

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## SUMMARY

Liquid hydrogen ($LH_2$) is being explored as a potential pathway toward achieving net-zero aviation emissions by 2050. However, its introduction will require significant redesign of aircraft systems, airport infrastructure, and ground handling procedures. This study presents a theoretical system safety analysis of $LH_2$-powered aircraft during ground operations, with particular emphasis on refuelling activities. Using System Theoretic Process Analysis (STPA), the research identifies system-level hazards, unsafe control actions, and potential loss scenarios within airport environments transitioning to $LH_2$ fuelling. The analysis highlights critical vulnerabilities related to communication, equipment integrity, environmental conditions, and human factors. The findings provide proactive safety insights intended to inform future airport design, training frameworks, and infrastructure investment strategies for $LH_2$ aviation integration.

## KEYWORDS

Liquid hydrogen; $LH_2$; ground handling; system safety; STPA; aviation human factors; hydrogen aviation

## Introduction

The aviation industry is under increasing pressure to reduce greenhouse gas emissions and achieve net-zero carbon targets by 2050. Among proposed technological pathways, liquid hydrogen ($LH_2$) has emerged as a promising alternative energy carrier due to its potential to significantly reduce carbon emissions when produced from renewable sources.

However, $LH_2$-powered aircraft are not yet operating commercially. Current developments remain at conceptual, demonstrator, and early prototype stages. The transition to $LH_2$ propulsion will require substantial changes not only in aircraft design but also in airport infrastructure, fuel storage systems, ground handling procedures, and regulatory frameworks.

Unlike conventional jet fuel, $LH_2$ must be stored at cryogenic temperatures (approximately −253°C), has low volumetric energy density, and requires specialised spherical or insulated tank designs. These characteristics introduce new operational challenges, particularly during ground handling and refuelling operations. As airports begin planning for hydrogen integration, understanding system-level safety implications becomes critical.

This paper presents a theoretical system safety assessment of $LH_2$-powered aircraft during ground handling operations. The primary focus is the refuelling process, as it represents the key differentiator between conventional aviation and $LH_2$ operations and introduces novel hazards related to cryogenic handling, vapour dispersion, and ignition risk.

## Background and Context

### *Current State of $LH_2$ Aviation*

At present, no $LH_2$-powered commercial passenger aircraft operate in scheduled service. Industry roadmaps suggest potential entry into service in the 2035–2040 timeframe, with broader integration aligned to 2050 decarbonisation goals. Therefore, this study is anticipatory and theoretical in nature.

### *Infrastructure Considerations*

Introducing $LH_2$ at airports requires:

- Cryogenic storage tanks
- Insulated transfer pipelines or tanker systems
- Dedicated $LH_2$-compatible parking bays
- Vapour detection systems
- Hydrogen-specific fire suppression capability
- Modified apron layouts to maintain separation distances

Unlike conventional fuel systems, $LH_2$ storage and distribution must account for boil-off gas management and vapour dispersion risks.

### *Operational and Cost Implications*

Infrastructure conversion represents a major capital investment. Costs include:

- Installation of cryogenic storage facilities
- Apron redesign and hazard zoning
- Specialised fuelling vehicles
- Staff retraining and certification
- Regulatory compliance adaptation

Additionally, $LH_2$ refuelling may require longer turnaround times due to volumetric considerations, potentially affecting airport capacity and revenue models.

Given these operational and systemic transformations, proactive safety analysis is essential before large-scale implementation.

## Method

STPA was chosen as the analytical method because it evaluates accidents as emergent system phenomena rather than solely attributing failures to human error. The analysis follows the steps outlined in the STPA Handbook by Leveson and Thomas (2018).

### *Nature of Study*

This is a theoretical systems analysis. No observational or empirical data were collected. The operational model was constructed using:

- Standard airport ground handling procedures
- Established ATC and pilot interaction frameworks
- Known technical characteristics of $LH_2$ systems
- Published hydrogen aviation feasibility studies

The purpose of the analysis is anticipatory: to identify hazards before commercial $LH_2$ implementation.

### *STPA Steps Applied*

The analysis followed four structured steps:

1. Define system losses, hazards, and safety constraints
2. Model the control structure
3. Identify unsafe control actions
4. Identify loss scenarios

The operational scenario modelled includes aircraft landing, taxiing to an $LH_2$-designated bay, passenger disembarkation, cargo handling, and $LH_2$ refuelling.

### *STPA Step 1 – Defining losses, hazards, and constraints*

Seven losses were identified, including injury or loss of life, damage to aircraft and ground vehicles, environmental harm, operational disruption, and reputational impacts. Nine associated hazards were defined, such as violation of minimum separation distances, incorrect parking, loss of fuelling integrity, and compromised human or equipment safety. System-level constraints were then established to ensure required separations, correct bay allocation, structural integrity, and safety in handling LH2 equipment.

### *STPA Step 2 – Modelling the control structure*

The operational scenario begins with air traffic control (ATC) issuing landing and taxi instructions. Pilots land and taxi to the designated LH2-compatible parking or refuelling bay, where ground crews prepare passenger disembarkation, cargo operations, safety equipment and LH2 refuelling systems. Controllers include ATC, pilots, ground crew, and passengers, each with defined responsibilities and feedback mechanisms. Elements such as refuelling trucks, fire safety vehicles, aerobridges, and cargo vans form part of the interacting system.

### *STPA Step 3 – Identifying unsafe control actions*

Unsafe actions were identified for ATC (e.g., incorrect clearances due to loss of situational awareness), pilots (e.g., incorrect bay taxi or runway misjudgement), ground crew (e.g., errors in refuelling, cargo handling, or bay preparation) and passengers (e.g., premature disembarkation prior to aerobridge connection). Each unsafe action was linked to potential hazards and system constraints.

### *STPA Step 4 – Identifying loss scenarios*

Loss scenarios arise from both human behaviours and system malfunctions. Examples include ATC communication failures or frequency interference, pilot misinterpretation of cockpit cues or radio issues, malfunctioning refuelling hoses or aerobridge systems, and environmental conditions such as rain or fog reducing apron visibility. LH2-specific risks, such as the consequences of fuelling line failure or undetected vapour leaks, were examined due to their high severity.

## Result

The analysis highlights that LH2 refuelling presents the most critical safety concern due to its flammability, cryogenic temperature requirements, and high sensitivity to leaks or disconnections. Past incidents involving conventional jet fuel, such as refuelling hose failures or vehicle collisions during low visibility, emphasise the need for robust LH2-specific safety protocols, enhanced training, and improved apron management.

### *Identified Losses*

Seven primary losses were identified:

- Loss of life or injury
- Aircraft damage
- Ground vehicle damage
- Operational disruption
- Environmental harm
- Infrastructure damage
- Reputational loss associated with hydrogen adoption

Reputational loss is particularly significant given $LH_2$'s early-stage adoption and public perception sensitivity.

### *Key Hazards*

Nine hazards were identified, including:

- Violation of minimum separation distances
- Incorrect parking bay allocation
- Loss of fuelling integrity
- Compromised human safety
- Equipment integrity failure
- Aircraft proximity to terminal during refuelling

Among these, loss of fuelling integrity (H4) was identified as the most critical hazard due to $LH_2$'s flammability and cryogenic properties.

### *Unsafe Control Actions*

Unsafe actions were identified across multiple controllers:

ATC

- Clearance given before runway is clear
- Incorrect parking bay allocation
- Communication timing errors

Pilots

- Taxiing to incorrect bay
- Misjudged separation distances
- Delayed or premature manoeuvres

Ground Crew

- Incorrect refuelling hose connection
- Failure to maintain safety perimeter
- Equipment misalignment

Passengers

- Disembarkation during refuelling
- Movement before aerobridge connection

### *Loss Scenarios*

Loss scenarios emerged from both human behaviour and system malfunction.

Human-Related Scenarios:

- Loss of situational awareness during apron operations

- Breakdown in communication between ATC and ground crew
- Improper sequencing of passenger disembarkation and refuelling

System Malfunction Scenarios:

- Refuelling hose failure or disconnection
- Vapour leak undetected due to odourless nature
- Aerobridge mechanical failure
- Sensor inaccuracies in proximity systems

Environmental factors such as rain, fog, snow, or reduced visibility further amplify these risks.

### *Key systemic vulnerabilities include:*

- High dependence on accurate communication between ATC, pilots, and ground crew
- Sensitivity of LH2 fuelling systems to equipment failure
- Increased risk from weather-related visibility issues
- The need for strict separation distances between aircraft, fuel trucks, and other equipment
- Potential for cascading failures if refuelling or bay allocation errors occur

## Discussion

### *Refuelling as the Primary Risk Concentration*

The analysis indicates that $LH_2$ refuelling represents the most critical safety vulnerability in ground operations. Unlike conventional fuel, $LH_2$ presents:

- Cryogenic burn risks
- Vapour cloud formation potential
- Ignition sensitivity
- Equipment material compatibility challenges

Even conventional jet fuel refuelling incidents (e.g., hose disconnections or apron collisions) demonstrate how seemingly minor failures can escalate rapidly. $LH_2$ increases potential severity.

### *Human Factors Considerations*

From a human factors perspective, $LH_2$ integration introduces:

- Increased cognitive load for ground personnel
- Novel emergency procedures
- Unfamiliar hazard cues (hydrogen is colourless and odourless)
- Higher coordination demands between ATC, pilots, and ground staff

Sustainable integration depends on:

- Cohesive CRM-based training
- Simulation-based emergency response preparation
- Error-tolerant equipment design
- Clear task sequencing protocols

If poorly implemented, $LH_2$ systems could increase workload and reduce situational awareness, undermining safety objectives.

### *Infrastructure and Organisational Readiness*

Safe $LH_2$ adoption requires more than equipment changes. It requires:

- Dedicated $LH_2$ apron zoning
- Automated vapour detection systems
- Cryogenic-compatible materials
- Specialised firefighting capability
- Regulatory adaptation and certification pathways

Airports must approach hydrogen integration as a systemic transformation rather than incremental modification.

### *Sustainability from a System Perspective*

From a human factors standpoint, sustainability extends beyond environmental impact. A fuel alternative is operationally sustainable only if:

- It does not increase human error probability
- It supports manageable workload
- It integrates within existing control structures
- It maintains public trust

Therefore, $LH_2$ viability depends on robust system design and organisational adaptation.

## Limitations

This study is theoretical and conceptual. No empirical data from operational $LH_2$ aircraft were available, as commercial $LH_2$ aviation has not yet commenced. The model assumes future implementation consistent with current hydrogen feasibility projections. Further research should incorporate simulation studies, cost modelling, and operational trials as data becomes available.

## Conclusion

This study applied STPA to evaluate system safety risks associated with $LH_2$-powered aircraft during ground handling operations. The analysis demonstrates that $LH_2$ integration introduces new system-level hazards, with refuelling emerging as the most critical risk domain.

Key findings include:

- High dependence on accurate communication across operational roles
- Sensitivity of $LH_2$ systems to equipment failure
- Increased cognitive and coordination demands
- Infrastructure redesign as a safety necessity rather than optional enhancement

Safe integration of $LH_2$ aviation will require:

- Comprehensive $LH_2$-specific training
- Enhanced communication frameworks
- Dedicated infrastructure investment
- Regulatory evolution
- Human-centred system design

Proactive safety analysis, such as STPA, is essential in enabling a safe transition toward hydrogen-powered aviation and supporting the broader net-zero aviation agenda.

## Future Research

Future research should examine:

- Cost-benefit modelling of $LH_2$ airport retrofitting

- Simulation-based evaluation of ground crew workload
- Comparative risk analysis between SAF and $LH_2$ operations
- Human reliability modelling under $LH_2$-specific scenarios
- Regulatory readiness assessments

Such research will support evidence-based implementation planning.

## References

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