

Human Factors Analysis and Classification System (HFACS) Applications in Transportation Human Factors: Review Study

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ABSTRACT

As transportation systems become increasingly complex, human factors remain critical to safety performance. The Human Factors Analysis and Classification System (HFACS) has become one of the most widely adopted frameworks for accident causation analysis, providing a structured approach to analyzing unsafe acts, preconditions, unsafe supervision, and organizational influences. This paper reviews HFACS applications in transportation research over the past 15 years. First, the theoretical foundations and core structure of HFACS are introduced, along with representative analytical methods commonly employed in accident analysis studies. Subsequently, HFACS applications are reviewed and compared across major transportation sectors, including aviation, rail transit, maritime transport, and road traffic. Finally, certain persistent challenges are identified, including ambiguous hierarchical boundaries, limited representation of dynamic risks, insufficient quantitative rigor, and relatively low information utilization efficiency. Future research may emphasize strengthening quantitative integration, enhancing multi-scenario adaptability, and incorporating data-driven and intelligent analysis techniques to strengthen proactive risk management in transportation systems.

Keywords: HFACS, Human factors analysis, Transportation safety, Accident prevention, Risk management

INTRODUCTION

With the rapid advancement of automation, digitalization, and system integration, modern transportation has evolved into a highly complex socio-technical system, in which human factors continue to play a critical role in safety. Studies indicate that accidents attributed to human factors account for 60%–80% of aviation accidents and up to 80%–90% of road traffic accidents (Ma, et al., 2022; He, 2009), which means human factors remain the primary cause of safety events.

Modern safety research has therefore shifted from purely technical reliability analysis toward human-centered and system-oriented approaches. Human decision-making, cognitive states, communication, organizational climate, and supervisory mechanisms are often critical in accident causation. Systematically identifying human-factor-related failures and implementing targeted interventions are essential for sustainable improvement in transportation safety management.

Received February 16, 2026; Revised April 9, 2026; Accepted April 29, 2026; Available online July 20, 2026

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In response to this need, numerous human factors analysis models have been developed for accident causation analysis. Among them, the Human Factors Analysis and Classification System (HFACS) has emerged as one of the most widely adopted frameworks. Originally developed for aviation and based on Reason's Swiss Cheese Model, HFACS provides a hierarchical taxonomy for identifying active failures and latent organizational conditions. Through its four-level structure—Organizational Influences, Unsafe Supervision, Preconditions for Unsafe Acts, and Unsafe Acts—HFACS enables systematic tracing of causal pathways across multiple system layers.

Over the past 15 years, the HFACS has expanded beyond aviation to rail transportation, maritime operations, road traffic, and other high-risk industries, with researchers increasingly integrating quantitative, data-driven, and AI techniques to enhance causal identification and risk analysis. (Nogueira et al., 2023; Declan et al., 2025).

This paper comprehensively reviews the current status of HFACS applications in transportation human factors research over the past 15 years and identifies the cross-domain patterns and domain-specific adaptations, followed by a discussion of current limitations and future development directions.

THEORETICAL FOUNDATIONS AND ANALYTICAL FRAMEWORK OF HFACS

Theoretical Origins: From the Swiss Cheese Model to Systemic Accident Analysis

HFACS is conceptually rooted in James Reason's Swiss Cheese Model of organizational accidents. Reason proposed that accidents in complex systems rarely result from isolated operator errors; instead, they emerge from the alignment of multiple latent failures and active errors distributed across organizational layers. Defensive barriers, represented metaphorically as slices of Swiss cheese, contain inherent weaknesses or "holes". When these weaknesses align, accident trajectories become possible.

This systemic perspective marked a significant departure from earlier linear and person-centered accident models. Rather than attributing accidents solely to frontline operator mistakes, systemic models emphasize the interaction between individual actions, supervisory practices, organizational processes, and environmental conditions. HFACS operationalizes this theoretical foundation by transforming abstract systemic principles into a practical classification framework suitable for empirical accident investigation and statistical analysis.

Core Structure of the HFACS Framework

The classical HFACS framework organizes accident causation into four hierarchical levels:

- **Unsafe Acts** – Direct actions of operators that lead to an accident, including errors (skill-based, decision, perceptual) and violations (routine or exceptional).

- Preconditions for Unsafe Acts – Environmental factors, operator conditions (e.g., fatigue, stress), and personnel factors (e.g., communication breakdowns) that shape frontline behavior.
- Unsafe Supervision – Inadequate supervision, inappropriate operational planning, failure to correct known problems, and supervisory violations.
- Organizational Influences – Resource management, organizational climate, and operational processes that create systemic vulnerabilities.

This hierarchical decomposition enables investigators to trace causal pathways from immediate operational behaviors to deeper managerial and organizational deficiencies. A key strength of HFACS lies in its ability to distinguish between active failures and latent conditions, facilitating identification of systemic corrective measures rather than merely individual blame.

Owing to this structured logic, HFACS has also been effectively integrated with probabilistic and relational modeling tools to enhance causal inference and risk prioritization (Wang et al., 2025; Meng et al., 2022).

Extensions and Domain-Specific Adaptations of HFACS

As HFACS has been applied beyond its original aviation context, researchers have introduced various extensions and adaptations to enhance domain suitability. These modifications typically involve:

- Refinement or redefinition of classification categories;
- Addition of new levels to address regulatory or environmental factors;
- Reorganization of subcategories to reflect operational characteristics;
- Integration with domain-specific safety management systems.

Examples include adaptations for maintenance operations, air traffic management, railway dispatching systems, maritime navigation in polar regions, and hazardous road transport.

Such extensions and adaptations improve explanatory resolution and intervention relevance (Huang, 2018; Wang et al., 2025). These developments reflect both the flexibility and contextual dependence of the HFACS framework.

Representative Analytical Methods in Accident Research

HFACS operates within a broader ecosystem of accident analysis methodologies. Representative approaches include:

- Fault Tree Analysis (FTA) – Emphasizes logical relationships between causal factors.
- Bayesian Networks (BN) – Enable probabilistic inference and uncertainty modeling.
- System-Theoretic Accident Model and Processes (STAMP) – Focuses on control structures and system constraints.
- Decision-Making Trial and Evaluation Laboratory (DEMATEL) – Identifies causal influence strength among factors.

- Failure Mode and Effects Analysis (FMEA) – Assesses risk priority through severity, occurrence, and detectability.
- System Dynamics (SD) – Models dynamic evolution of risks over time.

Compared with these approaches, HFACS primarily functions as a structured classification and diagnostic framework. It excels in organizing qualitative accident data and revealing hierarchical causal patterns but is less effective in modeling dynamic processes or conducting probabilistic inference. Consequently, hybrid approaches have emerged in which HFACS provides the causal taxonomy while complementary methods supply quantitative and dynamic modeling capabilities, such as HFACS-FTA for causal chain construction, HFACS-BN for uncertainty modeling, as well as integrations with DEMATEL, FMEA, and SD (Meng et al., 2022; Wu et al., 2023; Song et al., 2019; Liou et al., 2026).

APPLICATIONS OF HFACS ACROSS TRANSPORTATION DOMAINS

Over the past 15 years, HFACS has been widely applied across major transportation sectors, showing domain-specific emphases, methodological integrations, and adaptation patterns while sharing a common hierarchical logic.

Aviation

Aviation remains the most mature and extensively studied application domain of HFACS. Research has primarily focused on three areas: accident investigation, aircraft maintenance, and air traffic management.

In accident investigation, HFACS has been applied to general aviation accidents, commercial airline operations, helicopter crashes, and unmanned aerial vehicle incidents. Beyond identifying skill-based and decision errors, studies frequently reveal deeper supervisory and organizational contributors, such as inadequate training, regulatory gaps, and resource constraints.

In maintenance operations, HFACS has been used to classify maintenance errors, construct human error databases, and identify latent organizational deficiencies. Studies reveal that organizational influences and supervisory failures frequently form the upstream causes of frontline maintenance errors (Chen et al., 2022). Modified HFACS structures tailored to Maintenance, Repair, and Overhaul (MRO) environments have improved diagnostic precision.

Within air traffic control (ATC), effective communication between controllers and pilots, as well as accurate execution of instructions, is critical for safety. Research shows that unsafe acts by air traffic controllers are a significant contributor to civil aviation incidents (Pan et al., 2025). For instance, Gao et al. (2020) combined HFACS with Interpretive Structural Modeling (ISM) to identify 17 human factors in ATC, organizing them into a five-level hierarchical structure.

Overall, aviation applications demonstrate a shift from retrospective classification toward predictive and data-driven safety management.

Rail Transportation

In rail systems, HFACS has been employed to analyze dispatching errors, signaling failures, and construction incidents. Compared with aviation, rail studies often emphasize supervisory management and organizational coordination due to centralized operational control structures.

Researchers have developed rail-specific variants of HFACS and applied statistical techniques such as chi-square testing, association rule mining, and Grey Relational Analysis to explore inter-level correlations. For instance, Yang (2024) developed an HFACS-RAs model tailored to the railway sector based on 205 rail accident reports, using SPSS chi-square tests to identify inter-level correlations and the Apriori algorithm to extract association rules. Chen (2014) used HFACS to identify human factor hazards in high-speed rail dispatching and applied Grey Relational Analysis to 77 accident cases to assess factor correlations.

The rail domain demonstrates increasing methodological integration and quantitative emphasis.

Maritime Transportation

Maritime operations involve unique environmental uncertainties and multicultural crew dynamics. HFACS has been applied to analyze collision accidents, grounding events, polar navigation, and hazardous cargo transport. Quantitative extensions incorporating methods such as entropy weighting, TOPSIS, cloud models, and Bayesian inference have been used to evaluate factor importance and causal coupling.

For example, Yang et al. (2024) employed HFACS to identify factors influencing critical crew behaviors of polar navigation. They used a cloud model to convert fuzzy evaluations into quantitative parameters and determined the ranking of key factors by integrating the entropy weight–TOPSIS method. Zhang et al. (2019) analyzed collision accidents in polar ice zones, establishing an HFACS-based framework and fault tree model to evaluate ship collision risk under icebreaker escort.

Maritime adaptations often emphasize environmental and contextual preconditions due to variable sea states and operational isolation.

Road Traffic

In road traffic, HFACS has been applied to analyze commercial trucking accidents, hazardous material transport incidents, and large-scale traffic datasets. Compared with other domains, studies in road transport tend to focus more on driver behavior, violations, and decision errors.

Integration with methods such as the Analytic Network Process (ANP), Bayesian analysis, and data mining techniques has enabled the calculation of factor weights and the exploration of associations among contributing factors.

For example, Zheng et al. (2020) analyzed 201 truck accidents using HFACS integrated with ANP, chi-square tests, and odds ratio analysis to investigate the relationships among causative factors and their respective contributions. Zhang (2017) constructed a hazardous chemical transport accident database based on HFACS and applied R-based data mining, coupled with fault tree and Bayesian network analyses, to examine factor interactions and estimate accident probabilities.

Nonetheless, organizational-level analyses in road traffic lag behind those in aviation and rail sectors, likely due to differences in regulatory structures and the decentralized nature of operational control.

Cross-Domain Comparative Insights

Across domains, several common patterns emerge:

- Unsafe acts frequently appear as high-frequency immediate causes, but deeper supervisory and organizational deficiencies often drive systemic vulnerabilities.
- Quantitative integration has become a dominant methodological trend.
- Domain-specific adaptations are necessary to reflect operational structures and environmental characteristics.
- The availability of large-scale accident databases has been facilitated by the development of intelligent text mining and data-driven methods.

Meanwhile, differences exist in organizational influence weight, regulatory structures, and analytical focus. Aviation exhibits the most mature and standardized applications; rail emphasizes centralized management and dispatch systems; maritime highlights environmental uncertainty; road traffic concentrates more on individual driver behavior.

These cross-domain findings demonstrate both the versatility of HFACS and the necessity of contextual adaptation.

TRENDS, LIMITATIONS, AND DEVELOPMENT DIRECTIONS OF HFACS IN TRANSPORTATION

With the growth of transportation volume, system complexity, and global interconnectivity, human factors in transportation are evolving. Together with the rise of AI, big data, and networked technologies, HFACS has expanded toward data-driven and intelligent analysis. In this context, HFACS should not be viewed only as a retrospective framework for classifying human error, but also as a tool for analyzing interactions among operators, organizations, technologies, infrastructure, and regulatory systems within the broader global transportation ecosystem.

Recent studies have explored the integration of AI techniques with HFACS. For instance, Large Language Models (LLMs) have been combined with HFACS to support automated extraction of causal relationships from accident reports. Machine Learning (ML) methods have also been employed to enhance classification and prediction of unsafe acts based on HFACS-coded data (Harris et al., 2017). Moreover, HFACS is extending from retrospective

investigation toward proactive analysis, as shown in recent railway studies using safety inspection records.

However, several persistent challenges remain. First, may reduce coding consistency, as factors can overlap across individual, supervisory, and organizational levels. Second, HFACS has limited capacity to represent dynamic and evolving risks, especially in automated environments where human–automation interaction introduces patterns such as automation dependency and trust miscalibration. Third, quantitative rigor remains insufficient, as HFACS itself does not inherently quantify the relative contribution or probabilistic weight of different factors. The absence of standardized quantitative integration frameworks increases methodological variability across studies. Finally, traditional HFACS applications often pay limited attention to wider socio-technical influences beyond the organizational boundary, even though transportation safety is increasingly shaped by infrastructure, regulation, and cross-organizational coordination within the global transportation ecosystem.

Real-world cases illustrate these limitations. In the 2018 automated driving crash in Tempe, Arizona, the investigation identified operator distraction and broader deficiencies in safety risk assessment and oversight (NTSB, 2019). Similar patterns appear in rail, with communication failures and limitations in safeguards such as Positive Train Control (NTSB, 2023), and in maritime, where bridge resource management, fatigue, and cultural factors shape safety outcomes (TSB Canada, 2016). These cases indicate that HFACS should be linked more explicitly to real operations and the broader global transportation ecosystem.

To address these issues, future developments of HFACS may focus on three directions: enhancing quantitative integration with probabilistic modeling, data mining, and machine learning; improving cross-sector applicability through standardized yet flexible domain-specific extensions; and refining the representation of emerging human–technology factors, such as automation reliance, algorithmic bias, and human–AI collaboration. Closer integration with proactive safety management and inspection data may further extend HFACS from post-accident explanation to continuous operational safety improvement across the global transportation ecosystem.

CONCLUSION

This paper reviewed HFACS applications in transportation human factors research over the past 15 years, covering aviation, rail, maritime, and road transport. It highlighted common analytical patterns, domain-specific adaptations, and its continued role as a leading framework for structured accident causation analysis. Despite its widespread use, challenges persist, including ambiguous hierarchical boundaries, limited representation of dynamic risks, and insufficient quantitative rigor. Future research may emphasize strengthening quantitative integration, enhancing multi-scenario adaptability, and incorporating data-driven and intelligent analytical techniques. Through continued methodological refinement, HFACS may further improve its capacity to identify human and organizational factors

and provide stronger support for proactive risk management in increasingly complex transportation systems.

ACKNOWLEDGMENT

This research was supported by the National Key Research and Development Program of China (2023YFF0615902), and National Natural Science Foundation of China (71601007).

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