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A Comparative Study of Human Reliability Assessment using Success Likelihood Index Method (SLIM) and Human Error Assessment & Reduction Technique (HEART): A case study from a Boeing 737 Max Accident

M. Zaki Ramdhan[1], Daffa Abyan Rizq[1], Ayrton Senna[1], Adhitya Ryan Ramadhani[1*]

ABSTRACT

The accurate assessment of Human Error Probability (HEP) is crucial for aviation safety, especially in complex systems such as the Manoeuvring Characteristics Augmentation System (MCAS). This study compares two widely used human reliability analysis methods, HEART (Human Error Assessment and Reduction Technique) and SLIM (Success Likelihood Index Method), to evaluate their effectiveness in identifying and quantifying MCAS-related human errors. The results indicate that HEART is highly sensitive to human and organizational factors, as in Error Mode 5, where the calculated HEP is 0.164. In contrast, SLIM focuses more on system design and interaction reliability, yielding a significantly lower HEP of 0.0049. The comparative analysis highlights the strengths and limitations of each method, suggesting that a hybrid approach could improve the accuracy of human error assessments in aviation, leading to more effective risk mitigation strategies.

Keywords
HEART, Human Error, Human Reliability Analysis, MCAS, Probability, SLIM

[1] Department of Mechanical Engineering, Faculty of Industrial Technology, Universitas Pertamina
Jalan Teuku Nyak Arief, Jakarta Selatan 12220, Indonesia

* Corresponding Author: adhitya.rr@universitaspertamina.ac.id

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INTRODUCTION

Aircraft accidents remain one of the greatest challenges in the aviation industry and are often caused by a combination of technical factors, human errors, and unforeseen operational conditions. Despite technological advancements that have enhanced flight safety, accidents continue due to automation system failures, aircraft design flaws, and crew training limitations in emergency situations [1]. Human error, whether from pilots, technicians, or air traffic controllers, remains one of the dominant factors in many aviation incidents [2]. Therefore, it is essential to conduct an in-depth analysis of aviation accidents to understand the interaction between technology and human factors, as well as to develop more effective mitigation strategies to enhance flight safety. One concrete example of the complex interaction between automation technology and human factors is the crash of Lion Air Flight JT610 in October 2018. This accident was caused by the failure of the Maneuvering Characteristics Augmentation System (MCAS), an automated system designed to assist aircraft stability but instead caused the nose of the aircraft to pitch down due to erroneous sensor data [3].

The investigation revealed that MCAS relied solely on a single Angle of Attack (AoA) sensor without a backup system. As a result, when the sensor provided incorrect data, the system automatically adjusted the aircraft's trajectory without sufficient pilot intervention [4]. Furthermore, the lack of pilot training on MCAS worsened the situation, as the flight crew did not fully understand how to disable the system in an emergency [5]. This failure highlights the need for improvements in automation system design, increased sensor redundancy, and enhanced pilot training to ensure readiness in handling unexpected scenarios in the cockpit [6].

Another example of the complex interaction between automation and human factors is the crash of Ethiopian Airlines Flight ET302 on March 10, 2019 [7]. The Boeing 737 MAX 8 crashed just minutes after takeoff due to the activation of the MCAS system based on erroneous AoA sensor data. Similar to the Lion Air JT610 case, the pilots struggled to regain control due to insufficient training on the system. Additionally, the lack of redundancy in the design and the failure to provide adequate warnings to the flight crew further exacerbated the situation [4].

In aviation accident analysis, the Success Likelihood Index Method (SLIM) and the Human Error Assessment and Reduction Technique (HEART) are two quantitative methods within the Human Reliability Assessment (HRA) that can be used to evaluate the probability of human error systematically. SLIM is an expert-based method that assigns weights to various factors influencing task success, such as procedural complexity, time pressure, and the level of pilot training [8]. This approach enables a quantitative assessment of the likelihood of pilot errors when facing unexpected MCAS activation [9]. Meanwhile, HEART is a more flexible method designed to account for various operational conditions that may increase the likelihood of human error [10]. With HEART, factors such as high workload, non-intuitive system design, and pilots' lack of experience with new systems like MCAS can be analysed in greater detail to assess their impact on aviation safety [10].

In the context of the Boeing 737 MAX accidents, the SLIM approach can be used to evaluate the effectiveness of pilot training on automation systems and assess whether the flight crew was adequately prepared to handle emergency situations [11]. Meanwhile, the HEART method can help identify key risk factors that increase the likelihood of human errors, such as psychological pressure caused by the system’s continuous automatic corrections without sufficient warnings [10]. By combining these two methods, this research can provide a more comprehensive understanding of how human factors contribute to system failures and how improvements in design, training, and operational procedures can be implemented to prevent similar accidents in the future.

Previous studies, such as the FAA report (2020) [12], and case studies on MCAS failures [13], focused on the technical aspects of MCAS failures. These studies explored how the design and technical components of MCAS contributed to aircraft accidents. However, there is a gap in a more holistic approach, specifically in accident modelling, which considers the complex interactions between various factors [13]. This approach enables in-depth analysis of system dynamics, including technical failures, human behaviour, and operational conditions. Accident modelling can also be used to simulate scenarios and develop recommendations to prevent similar accidents in the future [14].

Unlike previous studies, this research compares two quantitative methods in Human Reliability Assessment (HRA), SLIM and HEART, to provide a more comprehensive evaluation of human error. This study analyses how MCAS failures, caused by technical errors, interact with human factors such as inadequate training and pilot workload. Through this approach, the research not only evaluates the technical aspects of the accidents but also examines how pilot training and system design influence responses to failures.

This study aims to conduct an in-depth analysis of the contributing factors in the Boeing 737 MAX accidents using the Human Reliability Assessment (HRA) approach. The primary focus is to identify and evaluate the contribution of human errors using two quantitative methods, SLIM and HEART, within the context of MCAS system failures. Additionally, this research assesses the probability of human error (Human Error Probability, HEP) occurring in the interaction between pilots, automation systems, and operational conditions during accidents.

Human Error Assessment and Reduction Technique (HEART)

The Human Error Assessment and Reduction Technique (HEART) is a widely used method for identifying, analyzing, and minimizing the likelihood of human errors in complex systems or processes [15]. By providing a quantitative approach to assessing Human Error Probability (HEP), HEART facilitates systematic calculations to evaluate how human factors influence overall system performance. This technique incorporates multiple human factor elements into risk assessment, thereby supporting better decision-making to improve operational reliability and human performance.

The first step in applying HEART is classifying tasks based on Generic Task Unreliability (GTU), where each task is assigned a predefined nominal HEP representing the baseline probability of failure under standard operating conditions. This classification allows for a structured assessment of human error risk. Following this, the identification of Error Producing Conditions (EPCs) is conducted to determine external, technical, or human factors that could amplify the likelihood of errors. Each EPC is assigned a multiplier effect, quantifying its impact on error probability.

To refine the analysis, an Assessed Proportion of Effect (APOE) is determined for each EPC, as not all EPCs contribute equally to task failure. The APOE value, ranging between 0 and 1, helps quantify the degree of influence each EPC has on a particular task. Subsequently, the assessed impact of EPCs is calculated using the following formula [16]:

$$Assessed\ impact = ((\max effect - 1) \times APOE) + 1 \tag{1}$$

Equation 1 measures the extent to which each EPC affects the probability of task failure. Finally, the overall HEP is computed using the formula [16]:

$$HEP = Nominal\ Human\ Unreliability \times \prod(Assessed\ Impact) \tag{2}$$

By integrating Equation 2, HEART provides a structured framework to systematically evaluate human reliability, enabling industries to develop targeted interventions that reduce human error and enhance operational safety.

Success Likelihood Index Method (SLIM)

The Success Likelihood Index Method (SLIM) is a quantitative technique used to assess the probability of human error in performing a specific task by analyzing the influencing factors [17]. This approach enables a systematic evaluation of human reliability within a given system by identifying, weighing, and quantifying the impact of each factor on task success.

The first step in SLIM is the identification of error modes, which refers to potential failures that may occur during task execution. This analysis involves detecting failure points and understanding external factors that could contribute to human error, providing insights into their impact on system reliability. Next, Performance Shaping Factors (PSFs) are identified and assessed, as these factors influence task success or failure. Each PSF is assigned a weight based on its level of influence, with the most critical factor receiving a weight of 100, while the others are scaled proportionally and normalized so that their sum equals 1.

Once the weights are assigned, the PSFs are ranked based on their contribution to task success. This ranking is independent of other factors and reflects expert evaluations of real-world task execution conditions. The Success Likelihood Index (SLI) is then calculated by multiplying each PSF ranking by its normalized weight and summing the results, producing a score ranging from 0 to 100. A higher SLI value indicates a greater likelihood of task success, whereas a lower value suggests a higher probability of failure. To determine the Human Error Probability (HEP), the SLI value is converted into the Probability of Success (POS) using the following logarithmic equation [16]:

$$Log(POS_i) = a(SLI)_i + b \quad (3)$$

In this Equation, the constants a and b are determined through scientific methods. Since frequency data for rare human errors may not always be available, the absolute probability estimation method relies on expert judgment to establish probability values for best-case and worst-case scenarios. After deriving the logarithmic value of POS, the Probability of Success is calculated as follows [16]:

$$POS = 10\ Log(POS) \quad (4)$$

Equation 4 is used to calculate the Probability of Success (POS) for the identified task, where the Log(POS) value is derived from Equation 3. Finally, the Human Error Probability (HEP) is determined using the equation:

$$HEP = 1 - POS \quad (5)$$

Equation 5 calculates the Human Error Probability (HEP). This equation indicates that HEP is obtained by subtracting POS from 1, representing the overall probability of human error in the analyzed task.

METHOD

This study employs the SLIM (Success Likelihood Index Method) and HEART (Human Error Assessment and Reduction Technique) methods to analyze the role of human error in Boeing 737 MAX accidents, particularly in relation to MCAS failures and pilot responses. In SLIM, error-causing factors are identified through Error Modes and Performance Shaping Factors (PSFs), such as high workload, lack of training, and complex system design. These factors are then weighted, rated, and used to calculate Human Error Probability (HEP). Meanwhile, HEART evaluates critical pilot tasks by determining Generic Task Unreliability (GTU) and assessing the impact of Error Producing Conditions (EPCs), such as time pressure and insufficient information on error probability. Figure 1 illustrates the methodological framework employed in this paper, outlining the key steps of the SLIM and HEART techniques used to assess Human Error Probability.

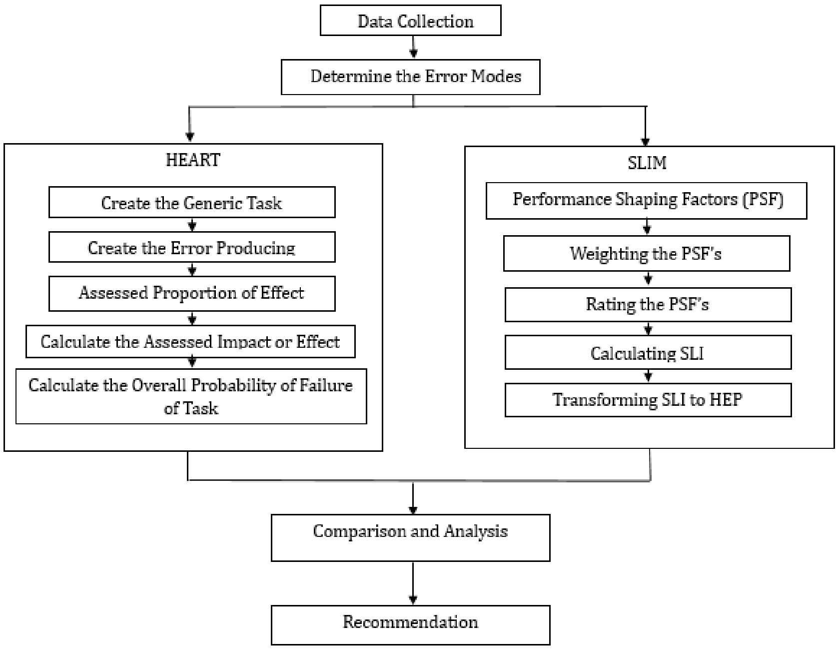

Figure 1. Conceptual Model

The process begins with data collection and error mode determination, followed by separate SLIM and HEART analyses. The results are then compared to provide a deeper understanding of the root causes of accidents. By integrating the findings from both methods, this study aims to offer recommendations for improving system design, pilot training, and operational procedures to mitigate human error and prevent similar incidents in the future.

RESULT AND DISCUSSION

This human reliability assessment, in the case of the Boeing 737 MAX accidents, provides Human Error Probability (HEP) calculations and key recommendations to enhance pilot training, system design, and operational procedures as a means of mitigating human error and improving aviation safety.

Result

As illustrated in Figure 1, the first step in this research is data collection to obtain essential information for achieving the research objectives. Data on the causes of the Boeing 737 MAX accidents were gathered from various sources, including accident investigation reports, pilot interviews, and safety evaluations of the MCAS system [18], as shown in Table 1.

Table 1. Error modes

NO	ERROR MODES	Reference
1	A single AoA sensor provided erroneous data to the MCAS, causing the system to point the nose of the aircraft downward when it was not necessary.	[19]
2	The MCAS is designed to rely on only one AoA sensor, with no redundancy to verify the data.	[12]
3	MCAS does not provide clear or timely notification to pilots when the system is active.	
4	Pilots do not receive special training on the function and handling of MCAS.	[3]

5	The aircraft certification process was accelerated to meet commercial deadlines, at the expense of an in-depth evaluation of MCAS safety.	[12]
6	Under high pressure, communication between the captain and copilot was not optimal to overcome the MCAS failure.	[3]
7	Repeated activation of MCAS adds significantly to the pilot workload, causing fatigue and decreased decision-making performance.	[5]

Table 1 presents several error modes identified in the failure of the MCAS system. Based on the collected data, the accident was analysed by categorizing failure causes into technical, human, and management factors. The next step involved conducting a Human Reliability Assessment (HRA) using SLIM and HEART methods to quantify the probability of human error and assess its impact on flight safety.

The initial step in the HEART (Human Error Assessment and Reduction Technique) calculation is to identify the Generic Task Unit (GTU) based on the predefined error modes listed in Table 1. This identification process is crucial as it establishes the foundation for further analysis by categorizing human tasks according to their likelihood of error occurrence. By accurately determining the GTU, the assessment can proceed with a more precise evaluation of human reliability, allowing for the application of appropriate error reduction techniques and ensuring a more comprehensive risk analysis.

Table 2. Generic Task and Max effect

NO	GTU	ERROR MODES	MAX EFFECT
1	GTU-H	A single AoA sensor provided erroneous data to the MCAS, causing the system to point the nose of the aircraft downward when it was not necessary.	0.00002
2	GTU-H	The MCAS is designed to rely on only one AoA sensor, with no redundancy to verify the data.	0.00002
3	GTU-H	MCAS does not provide clear or timely notification to pilots when the system is active.	0.00002
4	GTU-C	Pilots do not receive special training on the function and handling of MCAS.	0.121
5	GTU-C	The aircraft certification process was accelerated to meet commercial deadlines, at the expense of an in-depth evaluation of MCAS safety.	0.121
6	GTU-C	Under high pressure, communication between the captain and copilot was not optimal to overcome the MCAS failure.	0.121
7	GTU-F	Repeated activation of MCAS adds significantly to pilot workload, causing fatigue and decreased decision-making performance.	0.003

Table 2 classifies error modes based on Generic Task Unreliability (GTU) and their Max Effect values. Key errors include reliance on a single AoA sensor, lack of pilot training, and poor communication under pressure. These factors significantly impact the probability of failure, aiding in the Human Reliability Assessment (HRA) using the HEART method [18].

To calculate the Max Effect score in the HEART (Human Error Assessment and Reduction Technique) method, the process begins by identifying the relevant Generic Task Unreliability (GTU) value for a specific task. Each GTU category is associated with a baseline Human Error Probability [18]. Next, an Error Producing Condition (EPC) is determined, which reflects situational or contextual factors—such as lack of training, time pressure, or poor communication—that can increase the likelihood of error. Each EPC is assigned a standard multiplier based on empirical studies. The Max Effect is then calculated by multiplying the GTU base value by the full EPC multiplier, assuming that the EPC is fully active in the scenario (i.e., the assessed proportion of effect is 1). For instance, if the GTU is 0.01 and the EPC multiplier is 12.1 (e.g., for lack of training), the resulting Max Effect would be 0.121. This approach helps quantify the maximum possible impact of human error contributors on system reliability in a worst-case scenario [19].

Table 3 summarizes Error Producing Conditions (EPCs) in MCAS operations [20], detailing their impact on task failure. Each Error Mode is linked to a Generic Task Unreliability (GTU), with EPC values, APOE, and Assessed Impact quantifying their influence. The final HEP represents the overall failure probability. For the SLIM method, as shown in Figure 1, the first step is identifying the Performance Shaping Factors (PSFs). Based on the analysis of the error modes from Table 1, the key PSFs influencing the success of the evaluated task are identified.

Table 3. HEART Operational

Error Mode	GTU	EPC	EPC Description [20]	EPC value	APOE	Assessed impact	HEP
1	H	6	*“A mismatch between an operator’s model of the world and that imagined by the observer”*	8	0.4	3.8	1.72×10^{-4}
		13	*“Poor, ambiguous, or mismatched system feedback”*	4	0.3	1.9	
		14	*“No clear or timely confirmation of an intended action”*	3	0.1	1.2	
2	H	6	*“A mismatch between an operator’s model of the world and that imagined by the observer”*	8	0.6	5.2	1.95×10^{-4}
		19	*“No diversity of information input for veracity checks”*	2	0.2	1.2	
		3	*“A low signal-to-noise ratio.”*	9	0.07	1.56	
3	H	1	*“A low signal-to-noise ratio”*	17	0.4	7.4	4.62×10^{-4}
		7	*“No obvious means of reversing an unintended action”*	8	0.2	2.4	
		13	*“Poor, ambiguous, or mismatched system feedback”*	4	0.1	1.3	
4	C	4	*“A means of suppressing or overriding information or features that are too easily accessible”*	9	0.05	1.4	1.88×10^{-1}

Error Mode	GTU	EPC	EPC Description [20]	EPC value	APOE	Assessed impact	HEP
5	C	10	*"The need to transfer specific knowledge from task to task without loss"*	5.5	0.024	1.108	1.65×10^{-1}
		5	*"Ambiguity in the required performance standards"*	5	0.08	1.32	
		18	*"A conflict between immediate and long-term objectives"*	2.5	0.02	1.03	
6	C	8	*"A channel capacity overload due to simultaneous presentation of non-redundant information"*	6	0.06	1.3	1.59×10^{-1}
		26	*"No obvious way to keep track of progress during an activity"*	1.4	0.02	1.008	
7	F	10	*"Mental workload that exceeds individual capacity"*	9	0.7	6.6	2.24×10^{-2}
		26	*"No obvious way to keep track of progress during an activity"*	1.4	0.3	1.12	
		35	*"Disruption of normal work-sleep cycles"*	1.1	0.12	1.012	

Furthermore, The PSFs listed in Table 4 were ranked based on their weighted impact, demonstrating their their relative significance. Independent ratings reflect the actual conditions encountered during task performance, providing a foundation for Human Reliability Assessment using the HEART method.

Table 4. PSF Description

PSF	DESCRIPTION	Reference
Training Level	Inadequate MCAS training left pilots unprepared for unexpected system activations, contributing to the Lion Air JT610 accident.	[19]
Experience	Less experienced pilots struggled under high-stress conditions, increasing Human Error Probability (HEP).	[3]
Communication & Supervision	Effective guidance and communication play a critical role in reducing errors during operations.	
Environmental Condition	Factors like poor weather and operational challenges further impacted pilot decision-making and system performance.	[21]
Equipment and Tool Condition	Unreliable or malfunctioning equipment, including lack of redundancy in critical systems, heightened the risk of failure.	[13]

The process of calculating each SLI as illustrated in Table 5 involves multiplying the normalized weight of each PSF by its respective rating for each error mode and then summing the results. The SLI value ranges from 0 to 100, where 0 indicates a high probability of failure, and 100 represents a high probability of success in the analyzed task step.

Table 5. SLI Calculation Based on PSF Weight and Error Modes

PSF	Normalized Weight	EM 1	EM 2	EM 3	EM 4	EM 5	EM 6	EM 7
		P 1	P 2	P 3	P 4	P 5	P 6	P 7
Training Level	0.36	70	40	60	100	40	70	50
Experience	0.28	60	30	50	80	40	70	80
Communication & Supervision	0.18	80	60	70	60	80	90	60
Environmental Condition	0.036	30	10	20	10	60	60	20
Equipment and Tool Condition	0.143	50	80	40	40	60	20	40
SLI	0.999	64.63	45.4	54.64	75.28	50.74	66.02	57.64

Table 6 presents the Human Error Probability (HEP) calculation based on various error modes, with the best and worst estimates for each scenario. These calculations are based on the constants “a” and “b” used to determine the logarithm of the probability of success, which are further converted to probability of success and HEP. From the table, it can be seen that fault modes with a lower probability of success have a higher HEP, indicating a greater failure rate.

Table 6. SLI Calculation Incorporating PSF Weights and Error Mode HEP Values

Error Modes	Estimated HEP for the Best Case	Estimated HEP for the Worst Case	“a” Constant Value	“b” Constant Value	Log (Probability of Success)	Probability of Success	HEP
1	10^{-6}	10^{-2}	4.35×10^{-5}	-0.0043	-0.0016	0.9964	0.0036
2	10^{-8}	10^{-3}	4.34×10^{-6}	-0.0004	-0.0002	0.9994	0.0006
3	10^{-7}	10^{-1}	4.56×10^{-4}	-0.0457	-0.0207	0.9534	0.0466
4	10^{-9}	10^{-2}	4.36×10^{-5}	-0.0043	-0.0011	0.9975	0.0025
5	10^{-5}	10^{-2}	4.35×10^{-5}	-0.0043	-0.0022	0.9951	0.0049
6	10^{-3}	10^{-1}	4.53×10^{-4}	-0.0457	-0.0158	0.9642	0.0358
7	10^{-5}	10^{-2}	4.35×10^{-5}	-0.0043	-0.0019	0.9958	0.0042

Discussion

The comparative analysis between the SLIM (Success Likelihood Index Method) and HEART (Human Error Assessment and Reduction Technique) methods highlights critical differences in how each approach evaluates Human Error Probability (HEP) for different Error Modes (EMs) related to MCAS operations. As illustrated in the Figure 2, the results reveal that HEART generally estimates higher probabilities of error, particularly for factors associated with human and organizational elements, whereas SLIM places greater emphasis on technical aspects and human-system interactions.

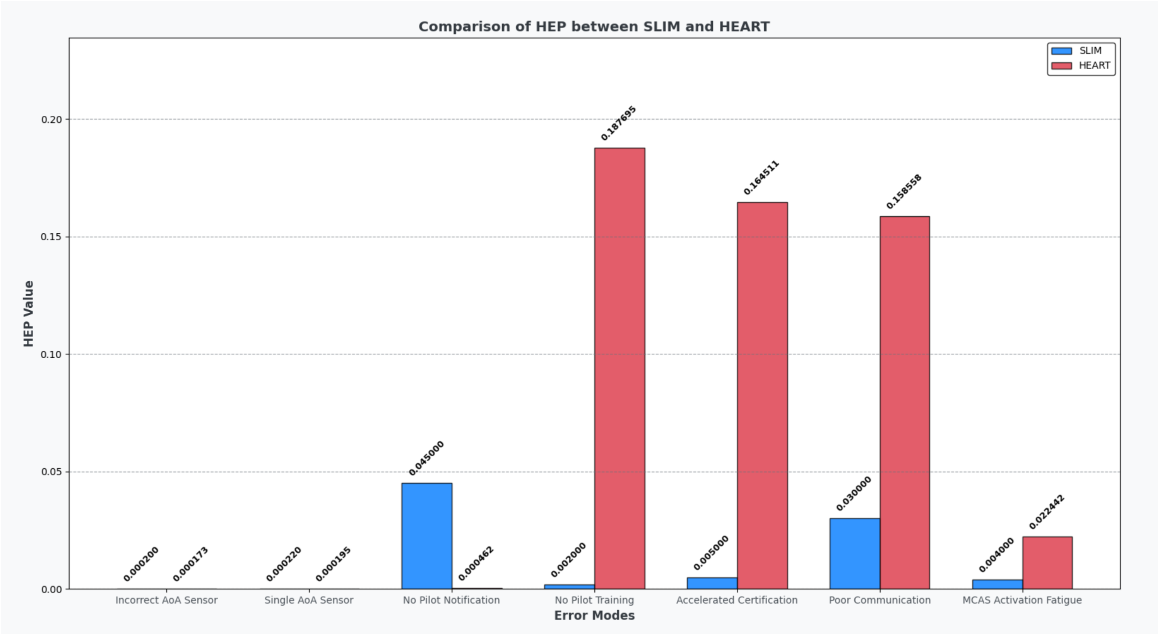

Figure 2. Comparison of HEP between SLIM and HEART

HEART tends to yield significantly higher HEP values for error modes associated with inadequate training (EM4), time pressure (EM5), and poor communication (EM6). This suggests that HEART is particularly sensitive to the organizational and psychological factors that can influence pilot performance, such as the level of training, operational stress, and coordination challenges. Conversely, SLIM provides higher HEP values for unclear system notifications (EM3) and communication failures (EM6), indicating a stronger focus on technical aspects and system feedback mechanisms.

A closer look at EM4 (Inadequate Pilot Training) shows that HEART assigns a very high HEP value (0.1877), reinforcing the notion that insufficient training on MCAS operations poses a significant risk. This finding aligns with industry concerns that a lack of specific, in-depth training contributed to previous MCAS-related incidents. The high HEART estimate suggests an urgent need for comprehensive pilot training programs, incorporating realistic simulations to mitigate operational errors. In contrast, SLIM assigns a much lower HEP value (0.0025), likely because its methodology does not emphasize human factors as strongly as HEART. While this lower value does not diminish the importance of training, it indicates that SLIM may underweight the human element in its assessments.

Similarly, for EM5 (Expedited Certification Process), HEART produces a high HEP value (0.1645), highlighting the risks associated with commercial pressures that may compromise safety in favour of production timelines. This serves as a warning to the aviation industry to avoid prioritizing efficiency over safety in regulatory and certification processes. SLIM, however, assigns a significantly lower probability (0.0049), suggesting that its assessment framework may not fully account for organizational and procedural factors such as time constraints imposed by market demands. This difference underscores the need to incorporate a holistic approach to risk assessment, balancing technical reliability with broader industry practices.

The case of EM6 (Suboptimal Communication) provides an interesting point of convergence between the two methods. Both HEART (0.1586) and SLIM (0.0358) assign relatively high HEP values, reinforcing the idea that poor communication among pilots is a major contributor to operational failures. This finding underscores the importance of improving technical and interpersonal communication protocols, ensuring that critical information is conveyed clearly and effectively during flight operations [22].

In contrast, the results for EM3 (Unclear or Untimely MCAS Notification) illustrate a stark divergence between the two methods. HEART assigns an extremely low HEP value (0.0004), which suggests that its framework is less sensitive to issues related to system feedback and notification clarity. This aligns with HEART's focus on human and organizational factors rather than technical system design issues. On the other hand, SLIM assigns a significantly higher probability (0.0466), reflecting a greater concern for how system notifications influence pilot decision-making. This result highlights an important insight: while human factors are crucial in error probability, system design and feedback mechanisms are equally critical in preventing operational failures.

These findings indicate that while HEART and SLIM provide valuable insights into human error analysis, they approach risk assessment from different perspectives. HEART offers a comprehensive evaluation of human and organizational influences, making it more suitable for identifying safety vulnerabilities in training, operational stress, and communication breakdowns. Meanwhile, SLIM provides a more technical and system-centric perspective, making it more effective for analyzing design flaws, system reliability, and human-machine interaction issues.

From an industry perspective, these results suggest that an integrated approach combining both HEART and SLIM may offer the most comprehensive risk assessment. By leveraging HEART’s sensitivity to human and organizational factors alongside SLIM’s ability to evaluate technical system failures, aviation safety frameworks can be more robust, balanced, and effective in mitigating human error. Future research should focus on validating these methods with empirical data from real-world flight incidents, ensuring that error probability models accurately reflect operational realities.

CONCLUSION AND RECOMMENDATION

Conclusion

The comparison between HEART and SLIM in assessing Human Error Probability (HEP) for MCAS-related errors highlights key differences in their focus. HEART emphasizes human and organizational factors, assigning higher HEP values to inadequate training, time pressure, and communication failures, making it useful for policy and training improvements. SLIM, on the other hand, prioritizes technical and human-system interaction issues, such as unclear notifications and automation reliability, making it valuable for system design enhancements.

Recommendation

The findings suggest that no single method is entirely comprehensive; a hybrid approach integrating both HEART and SLIM would provide a more balanced risk assessment. Given the complexity of aviation safety, regulatory bodies should adopt both methods to strengthen pilot training and improve system design. Future research should validate these methodologies using real-world data and explore machine learning integration to enhance HEP prediction accuracy.

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