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Conceptual Design of Vehicle Indicator Panels: An Educational Framework for Teaching Safety, Human–Machine Interaction, and Systems Engineering

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ABSTRACT

This paper develops a conceptual design methodology for vehicle indicator panels and situationally color-changing display systems while positioning these engineering concepts as pedagogical tools for science and engineering education. As automation and cyber-physical transportation systems advance, students and trainees must acquire competencies in safety engineering, human–machine interaction, real-time decision-making, and system interface design. The study examines the functional principles of indicator panels, formulates a conceptual design method, and establishes optimization criteria relevant to both engineering practice and instructional settings. Using system engineering, ergonomic design, communication theory, and ontological analysis, the research models information processing in normal and abnormal operating conditions. The resulting methodology not only supports safer interface development but also provides an educational framework for integrating conceptual modeling, risk analysis, and interface design into engineering curricula. The novelty of this work lies in linking indicator panel design with science education by transforming a complex engineering task into a structured learning model that enhances students' understanding of system behavior, safety logic, and the cognitive dimensions of human–machine interaction.

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1. INTRODUCTION

The rapid expansion of unmanned and human–machine transportation systems demands not only technological innovation but also new approaches to science and engineering education (Barmpounakis *et al*., 2016; Zhang *et al*., 2017). As vehicles evolve into complex cyber-physical systems, ensuring safety and operational efficiency increasingly depends on users' ability to interpret dynamic information from indicator panels and respond appropriately in real-time conditions. Thus, the conceptual design of vehicle indicator panels is no longer solely an engineering challenge but also an educational imperative for preparing future engineers, operators, and system designers. Strengthening competencies in human–machine interaction, ergonomic decision-making, risk perception, and interface interpretation is essential for modern STEM and engineering curricula, particularly as these competencies influence both system safety and user cognitive performance.

Within this context, the relevance of the present study arises from the need to formulate a methodological framework for teaching and understanding indicator panel design as a foundational component of transportation system safety. Developments associated with the Fourth Industrial Revolution highlight the increasing automation of vehicles, the expansion of unmanned mobility, and the intensifying reliance on integrated human–machine systems. For learners in engineering and applied sciences, this shift necessitates educational tools that provide conceptual clarity on how information is structured, visualized, and cognitively processed during normal and abnormal operating conditions. Consequently, the conceptual design of indicator panels becomes a critical pedagogical gateway for introducing students to safety engineering, systems thinking, real-time control, and interaction design principles.

The central problem addressed in this study is the need to enhance both safety and efficiency in human–machine transportation by constructing indicator panels that support effective operator decision-making. Simultaneously, engineering education lacks structured instructional frameworks that translate these complex design processes into clear, learnable concepts for students. By examining indicator panels as interfaces that mediate cognitive, technical, and organizational behavior, this research provides an educationally relevant model for teaching real-time control processes, hazard recognition, and information reduction under uncertainty. Previous work has emphasized that transportation systems always contain at least one uncontrolled operational outcome, reinforcing the importance of adequate information flow to prevent unsafe states and making system behavior modeling essential for STEM instruction.

A review of relevant literature further supports the educational significance of conceptual indicator panel design. Studies on human–machine interfaces demonstrate the need to understand ergonomic principles and operator processing speed when designing cognitive interaction environments (Sverchkov, 2018). Research on conceptual design methodologies highlights the importance of early-stage structural abstraction and modeling—skills that directly benefit engineering students learning system architecture and software-interface integration (Sviridenko & Yeshenko, 2018). Additional findings on open-architecture computing platforms reveal how interface constraints and information processing requirements shape users' operational awareness, underscoring the need for such concepts to be included in engineering and science education (Fedoseev, 2016). Collectively, these contributions reinforce that conceptual design is not only a technical activity but also a pedagogical tool for cultivating systems thinking, ergonomic awareness, and cognitive readiness—competencies increasingly required in advanced transportation technologies.

Accordingly, based on our previous studies in managing engineering education (Glushchenko, 2019; Glushchenko, 2021; Glushchenko, 2023; Glushchenko, 2024; Glushchenko, 2025), the aim of this study is twofold: (i) to develop a methodological framework for the conceptual design of indicator panels in vehicles and transportation systems, and (ii) to contribute to science and engineering education by transforming this methodology into a pedagogical model that supports learning about human-machine interaction and safety-critical information processing. The research tasks include analyzing the essence and functional roles of indicator panels, synthesizing a design methodology grounded in situational analysis and ergonomic principles, discussing methodological elements applicable to instructional settings, and formulating optimization criteria useful for both engineering practice and STEM education.

Overall, the conceptual approach presented in this study advances interface design for modern vehicles while simultaneously enriching educational practices by offering a structured, theory-based model that educators can integrate into engineering, safety, and human–machine systems curricula. This dual contribution affirms the relevance of the research within both technological development and contemporary science education.

2. METHODS

The methodological foundation of this study is based on modeling the functioning of vehicles and transportation systems as complex human–machine structures, which provides an analytical basis both for engineering practice and for science education. Conceptual design of vehicle indicator panels is approached as a learning-oriented framework that enables students and practitioners to understand system behavior, uncertainty, information processing, and safety logic. The methodology integrates system engineering, ergonomic design, communication theory, structural analysis, ontological modeling, organizational behavior theory, and safety analysis. Within the context of engineering education, these methods form a pedagogical toolkit that supports training in human–machine interaction, cognitive ergonomics, and real-time control.

The method begins with graph modeling of transportation processes, which reveals that every vehicle's operation includes at least one uncontrollable outcome. This conclusion is derived from a model containing two functional outcomes—normal operation and operation failure—and two information conditions—availability or lack of information. The four resulting states are:

(i) normal operation with information available,
(ii) normal operation without information,
(iii) failure with information available, and
(iv) failure without information.

The fourth state, characterized by failure and information absence, produces operational hazard. This theoretical insight is highly relevant for educational purposes because it illustrates to learners that uncertainty is an inherent property of complex cyber-physical systems, and thus must be addressed through interface design.

A key methodological element is the formal definition of real-time control, which is essential in teaching students how vehicles transition from permissible to dangerous states. In the experiments referenced, failures of unmanned aerial vehicles allowed the formulation of a probabilistic criterion for real-time control:

A system operates in real time if the time required to form and implement a control action does not exceed the time during which the vehicle transits from a permissible state to an unacceptable state with probability greater than a specified threshold.

The probability of maintaining the vehicle within permissible states is expressed through the following equations (1) and (2):

$$R_{od}(t, t_y) = \min\ P_{ei}(t, t_y) \quad (1)$$

$$R_{od}(t, t_y) = \int_{\pi_{\min}}^{\pi_{\max}} f(\pi)\, d\pi \quad (2)$$

where

- $i = 1, \dots, n$= number of vehicle parameters,
- $P_{ei}(t, t_y)$= probability that the i-th parameter remains within permissible bounds,
- $\pi_{\min}, \pi_{\max}$= minimum and maximum rates of change for each parameter under which the system remains safe,
- $f(\pi)$= density function of the rate of change of parameter πduring abnormal situations.

Real-time control is satisfied if shown in equation (3):

$$R_{od}(t, t_y) > R_{zad} \quad (3)$$

where $R_{zad}$is the minimum acceptable safety probability.

Introducing these formulas into engineering education strengthens students' understanding of safety thresholds, probabilistic risk, and dynamics of cyber-physical systems.

Experimental studies of operator behavior show that human controllers can be modeled as an aperiodic link with a 0.1-second lag, meaning cognitive processing speed is directly influenced by indicator panel architecture. This insight reinforces the teaching of ergonomic principles and the importance of interface clarity in high-risk decision environments.

The method proceeds by defining the conceptual model of an indicator panel as a simplified representation used to teach and evaluate the design logic of human–machine interfaces. This includes:

(i) segmentation of users based on psychophysical characteristics,
(ii) mapping normal and abnormal reading situations,
(iii) modeling operator behavior, and
(iv) defining panel functions and roles.

Such steps form an educational algorithm demonstrating how interface concepts are systematically developed.

The research further integrates interaction design theory, which is valuable for instruction because it teaches students to approach panel design from a user-centered perspective. In addition, ontological analysis is used to structure conceptual relationships among display elements, helping learners conceptualize indicator panels as interdependent information subsystems.

From a methodological perspective, the study also includes procedures for optimizing telemetry distribution, a task that introduces students to diagnostic reasoning and probabilistic modeling. The optimization problem is defined as distributing a limited number of telemetry channels to maximize the probability of correct failure diagnosis in systems that may contain tens of thousands of elements. This demonstrates to students the constraints of real engineering environments and the need for intelligent parameter prioritization.

Together, these methods construct a dual-purpose framework:
(i) An engineering methodology for designing safe, ergonomic indicator panels.
(ii) An educational model for teaching safety engineering, systems thinking, interface logic, and cognitive ergonomics within science and engineering education.

3. RESULTS AND DISCUSSION

The results of the conceptual and analytical investigation reveal that indicator panels serve as foundational components in both vehicle safety systems and science-engineering education. The modeling of operational outcomes demonstrates that transportation systems, regardless of their level of automation, will always contain at least one uncontrolled state, indicating an inherent structural uncertainty in cyber-physical systems. This insight is pedagogically important because it illustrates to students how uncertainty, information gaps, and abnormal states arise naturally in real-world system behavior. In engineering education, this forms a conceptual anchor for teaching risk assessment, decision thresholds, system monitoring, and interface demands in human–machine systems.

One of the central findings of the study is the identification of information delay and cognitive processing limits as major determinants of safety in man-machine systems. Operators can be mathematically modeled as an aperiodic link with a delay of approximately 0.1 seconds, implying that any increase in information complexity or poor ergonomic arrangement of indicators directly increases decision latency (Sverchkov, 2018). This finding reinforces the educational necessity of integrating cognitive ergonomics into STEM curricula, particularly in courses that teach interface design, real-time control, and applied human factors. Students learning system design must understand that the layout, color scheme, contrast, and clustering of information affect not only usability but also the measurable probability of system failure.

From an analytical standpoint, the conceptual model developed in this research demonstrates that indicator panels must reduce uncertainty by presenting only the most relevant and safety-critical parameters. Because a vehicle may have up to 10,000 components, it is pedagogically impossible—and practically unsafe—to display every parameter in real time. Therefore, engineering students must be trained in **information reduction principles**, prioritization of diagnostic indicators, and telemetric channel allocation. This is especially important in laboratory-based education where students design or simulate systems with constrained bandwidth, processing time, or cognitive load.

A comparative framework has been developed to illustrate the functional and educational implications of indicator panel design across three dimensions: safety, cognitive demand, and instructional value. This comparison not only guides engineering practice but also supports curriculum development in science and engineering education. **Table 1** presents the synthesized findings.

The results also highlight that conceptual design must incorporate situational color changes as a safety enhancement mechanism. Color-coded alerts—green for normal conditions, yellow for caution, and red for critical danger—were found to effectively lower the probability of misinterpretation by operators. In educational environments, this principle translates into a valuable demonstration of how perception psychology intersects with engineering design. Students exposed to such models develop a deeper understanding of how visual encoding improves reaction speeds and reduces decision errors, a key competency in fields such as robotics, aviation, and automotive engineering.

Another important result concerns the conceptualization of the indicator panel as an interface representing the "image" of the vehicle. This includes not only technical status but also the broader perception and brand identity associated with the system. Interfaces are not neutral—they shape user behavior, satisfaction, and trust. From a Science Education perspective, this widens the pedagogical scope by linking engineering design with communication theory and user-centered thinking. It allows students to see how technical and aesthetic decisions jointly influence human–machine interaction and organizational identity.

Table 1. Functional, Safety, and Educational Roles of Indicator Panels

Dimension	Engineering Function	Safety Contribution	Educational Value
Information Structuring	Organizes technical data into readable visual segments	Reduces uncertainty and prevents unnoticed failures	Teaches data hierarchy, systems thinking, and interface logic
Color Coding	Highlights urgency through visual contrast	Provides rapid hazard recognition during abnormal states	Demonstrates cognitive ergonomics and perception-based design
Parameter Selection	Limits display to critical metrics	Prevents distraction and mitigates overload	Introduces principles of information reduction and prioritization
Real-Time Responsiveness	Ensures timely feedback loops	Prevents transition to unsafe system states	Models real-time control in engineering education
Telemetry Integration	Enables remote monitoring	Enhances diagnostic accuracy	Teaches students about data acquisition and cyber-physical connectivity

Furthermore, the analysis reveals that designing effective indicator panels requires segmenting drivers or operators based on their psychophysical characteristics. This finding has strong implications for education because it supports the teaching of learner diversity, user modeling, and inclusive engineering design. Students must learn that different users—novice drivers, professionals, older adults—process information differently, and thus interface architecture must accommodate diverse cognitive preferences. Integrating such discussions into engineering laboratories enhances students' awareness of human variability in system interaction.

The algorithmic sequence proposed for conceptual design—user segmentation, situation mapping, behavioral modeling, function definition, and architectural synthesis—serves not only as a design method but also as an instructional sequence for problem-based learning. When embedded in classroom activities, students can perform conceptual modeling exercises, evaluate hazard scenarios, propose display arrangements, and test their designs through simulation software. This aligns with the active learning approaches increasingly promoted in modern STEM education.

A significant methodological outcome is the identification of protocols for data exchange between the vehicle and the operator as foundational elements of system safety. These protocols define how information flows, how it is timed, and how it is contextualized, directly influencing decision accuracy. In educational contexts, studying such protocols allows students to understand systems architecture, communication latency, and data integrity—concepts central to cyber-physical system design.

The results also support the classification of indicator panel design as an intelligent project management task, since engineers must optimize limited telemetric channels while maximizing diagnostic probability. This introduces students to statistical reasoning, optimization under constraints, and reliability analysis. Reducing uncertainty is the essence of information value, and teaching this principle helps students understand why interface clarity is a safety requirement rather than a stylistic choice.

The necessity to distribute telemetry channels optimally provides a gateway for teaching game theory and probability modeling. When telemetry is scarce, as in real experiments, students can model failures either as probabilistic events with historical distributions or as game-theoretic outcomes in single-operation uncertainty. This develops analytical thinking and strategic reasoning—key learning outcomes for engineering education programs worldwide.

The results further emphasize that conceptual design of indicator panels is inseparable from the broader architecture of human–machine systems. Because indicator panels serve as the cognitive gateway between the operator and the transportation system, their design influences information flow, perception accuracy, and ultimately behavioral outcomes during normal and abnormal operations. These findings reinforce the educational value of introducing conceptual panel design into STEM curricula, particularly in engineering programs that teach cyber-physical systems, real-time monitoring, and safety engineering. When students study indicator panels as structured information ecosystems rather than isolated visual components, they develop stronger systems-thinking competencies and a deeper understanding of how information architecture affects decision outcomes.

A key outcome of the analysis concerns the psychological dimension of interface design. As noted in the original work, elements such as layout, color, typography, and corporate identity influence not only readability but also user confidence, stress levels, and mode of interaction. These characteristics make indicator panels an excellent instructional example for teaching affective engineering, cognitive ergonomics, and human factors psychology. Through laboratory experiments, simulations, or eye-tracking studies, students can investigate how design choices influence error probability and reaction time. Such activities strengthen educational outcomes by transforming theoretical concepts into observable human responses.

Another important result relates to the design of situational color-changing panels, which provide intuitive cues to operators by visually classifying system states into safe, cautionary, and critical categories. From an instructional perspective, these panels demonstrate the fusion of engineering logic and perceptual psychology, enabling learners to grasp how multimodal cues (color, alarms, voice prompts) work together to improve situational awareness. This blended-cue design offers rich opportunities for interdisciplinary teaching that combines engineering, science education, and behavioral studies. Students can analyze case scenarios, compare the effectiveness of different color logics, and design improved prototypes that align with human cognitive constraints.

To support instructional clarity, **Table 2** has been developed to map the pedagogical relevance of each conceptual design element in the study.

The analysis also demonstrates that indicator panels act as instruments for shaping organizational impression and brand identity. While this may appear peripheral to engineering design, the aesthetic and symbolic components of interfaces hold significant instructional value. They allow educators to illustrate how engineering solutions must communicate meaning, reassure users, and integrate into larger sociotechnical environments. As vehicles evolve into connected, intelligent systems, panel design becomes a medium through which engineering students can learn communication theory, cultural considerations, and multimodal representation.

The final insight concerns the increasing role of intelligent project management in panel design. Because real-world engineering constraints require balancing limited telemetry channels, competing information demands, and uncertain failure scenarios, students benefit from learning to think in terms of constraints, trade-offs, and probabilistic outcomes. Incorporating these conceptual design challenges into science and engineering education nurtures analytical flexibility and prepares learners for real-world system development tasks.

Table 2. Pedagogical Implications of Conceptual Indicator Panel Design

Conceptual Element	Engineering Purpose	Educational Benefit	Example Learning Activity
Situational Color Changes	Prioritizes hazard visibility	Teaches perception and cognitive load theory	Testing reaction times to color-coded alerts
Telemetry Channel Optimization	Maximizes diagnostic accuracy	Teaches probability, optimization, systems reliability	Designing telemetry allocation strategies
User Segmentation	Tailors interface to psychophysical traits	Introduces inclusive design & user modeling	Creating personas for interface redesign
Interaction Design	Enhances intuitive operator behavior	Teaches client-centered engineering thinking	Redesigning layouts based on behavior mapping
Ontological Modeling	Structures conceptual relationships	Teaches conceptual clarity and system abstraction	Building concept maps of panel architecture

Overall, the results confirm that conceptual indicator panel design contributes not only to technological advancement but also to science education by providing rich, interdisciplinary learning opportunities. The integration of ergonomic analysis, cognitive psychology, system modeling, and safety engineering into a single conceptual design task demonstrates the powerful role of engineering artifacts as educational tools. By studying and designing such systems, students develop both the technical and cognitive competencies required for modern human–machine interaction environments.

4. CONCLUSION

This study demonstrates that the conceptual design of vehicle indicator panels is fundamental not only for advancing the safety and efficiency of human–machine transportation systems but also for strengthening science and engineering education. The analytical results confirm that indicator panels function as critical cognitive interfaces, shaping operator decision-making, perception speed, and real-time system responsiveness. By modeling operational uncertainty, information delays, and safety thresholds, the research provides a structured methodology that can be incorporated into STEM learning environments to enhance students' understanding of system behavior, cognitive ergonomics, and interface logic.

The introduction of situational color-changing panels and optimized information architectures illustrates how engineering principles can be translated into educational tools that cultivate systems thinking, risk awareness, and human-centered design competencies. Furthermore, the methodological sequence (user segmentation, behavioral mapping, parameter selection, and conceptual modeling) offers a pedagogical framework suitable for project-based learning and interdisciplinary instruction. Overall, the findings affirm that conceptual indicator panel design serves as an effective bridge between engineering practice and science education, providing learners with the analytical, cognitive, and technical skills required for future work in human–machine interaction and cyber-physical transportation systems.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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