



## Transportation Safety Engineering and Risk Mitigation Systems

Stanislav Chuikov  <sup>1</sup>\*

<sup>1</sup> Volodymyr Dahl East Ukrainian National University, Kyiv (Ukraine). Specialist Degree in Mechanical Engineering, Specialist Degree in Enterprise Economics. Head of the Motor Transport Division, LLC “Luhanskvoda”

\* Corresponding Author, e-mail: [slava0386@ukr.net](mailto:slava0386@ukr.net)

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### ABSTRACT

This paper aims to substantiate a deterministic, engineering-first approach to incident prevention in industrial logistics and freight transport, where heavy vehicles, pedestrians, and dense maneuvering zones create high-consequence risk. The study employs a systems-engineering and cybernetic risk-management approach, using comparative analysis of safety architectures (from passive barriers to integrated digital ecosystems), cognitive-ergonomics reasoning to address warning effectiveness and alarm fatigue, and reliability engineering methods (P–F interval logic, FRACAS feedback, and condition-based maintenance) to connect operations with predictive control. A 15-year operational retrospective from an enterprise fleet (350 units of specialized heavy machinery) is used to assess changes in near-miss dynamics after deploying the proposed controls. Results indicate that coupling smart infrastructure (flow segregation and proximity enforcement via UWB/LiDAR/radar and dynamic projection), vehicle-level assistance (ADAS, sensor fusion, and V2X-type messaging), and predictive diagnostics (IoT monitoring and digital-twin-supported anomaly detection) reduces exposure to conflict scenarios while improving operational continuity. Scientific novelty lies in the author’s proprietary “Chuikov’s Multi-Contour Safety System” as a unified interaction algorithm across the man–machine–environment triad, including a haptic feedback protocol (seat/steering vibration) that replaces non-actionable acoustic alarms in high-noise environments. The practical value is a transferable technical roadmap for designing, implementing, and auditing safety controls at industrial sites, enabling safety to be managed as an engineered process rather than a probabilistic outcome. The paper notes deployment constraints (cost, legacy integration, and AI liability) and indicates directions for further research.

### KEYWORDS

transportation safety engineering, Advanced Driver Assistance Systems (ADAS), Digital Twins, V2X technologies, Condition-Based Maintenance (CBM), Sensor Fusion, FRACAS.

## Introduction

In the current realities of industrial and logistics ecosystems ensuring safety is a fundamental engineering task directed at managing entropy in complex technical systems, where colossal kinetic energy, the human factor and variable environmental conditions interact (Dhillon, 2012). A profound understanding of operational processes requires abandoning the perception of accidents as an inevitable statistical randomness in favor of the concept of incident determinism, where each failure is preceded by a chain of detectable technical prerequisites (Kletz, 2020).

Questions of engineering control acquire particular criticality in the sphere of operating heavy-duty freight transport at critical infrastructure facilities. Unlike the commercial passenger segment, safety failures here threaten national supply chain stability. The safety of specialized machinery becomes an integral part of operational reliability: any latent defect of hydraulics, fatigue failure of load-bearing structures or failure of the braking system in the conditions of an industrial facility carries the potential for catastrophic damage (Fonseca & Ferreira, 2025). Consequently, technical protection strategies must be integrated at the level of the machine architecture and its maintenance processes, creating an echeloned defense against failures working both in standard mode and under peak loads (Smith & Simpson, 2020).

Considering the vehicle in isolation from the infrastructure in which it functions is methodologically erroneous. Industrial sites and logistics hubs represent saturated zones of increased danger, where the movement trajectories of machinery and personnel constantly intersect. The engineering infrastructure of enterprises must act as an active element of the safety system capable of leveling operator errors and preventing collisions through the implementation of technical barriers and automated access control systems. Nevertheless, a unified “human - machine - environment” safety contour is formed, the stability of which depends on the reliability of each constituent element (Manzoor et al., 2025; Hollnagel, 2014).

In this context the maintenance paradigm undergoes radical changes. Modern approaches are based on continuous monitoring of machinery “health”, where the analysis of vibrations, temperature regimes and operating parameters allows identifying component degradation at early stages. The role of engineering control transforms into the creation of an intelligent environment capable of predicting failures, which allows translating safety from the category of probabilistic variables to the category of managed engineering processes guaranteeing the continuity and security of transport operations (Jardine et al., 2006).

## Literature Review

Dhillon treats safety as an engineering discipline that must explicitly integrate human error analysis with technical risk assessment, offering approaches and examples of how operator actions, interfaces, and system operating conditions jointly shape accident causation in complex engineering systems (Dhillon, 2012). Kletz, drawing on practical industrial safety engineering, uses applied cases to show that incidents often arise when systems are designed without sufficient “tolerance” for predictable human mistakes, and he substantiates the principle of designing for error - designing with errors in mind through layered protection and more forgiving operational conditions (Kletz, 2020). Hollnagel deepens this logic by contrasting Safety-I (preventing things from going wrong by reducing failures) with Safety-II (understanding why things usually go right due to adaptive performance), thereby reframing safety as a property of socio-technical resilience rather than merely compliance with rules (Hollnagel, 2014). In parallel, Smith and Simpson synthesize the safety-critical systems perspective and functional-safety logic (the IEC 61508 family of standards), emphasizing structured hazard analysis, verification/validation, and lifecycle governance so that safety functions deliver predictable risk reduction under real operating conditions (Smith & Simpson, 2020). For transport operations, Fonseca and Ferreira, in a systematic review of truck driver monitoring technologies, show how multimodal sensing approaches (vehicle telemetry, cameras, wearables) are used to track fatigue/distraction and to link these indicators to safety outcomes and intervention strategies (Fonseca & Ferreira, 2025); Lohani, Payne, and Strayer review psychophysiological measurements in “real-world” driving, clarifying which biomarkers can (and

cannot) reliably reflect attention, cognitive workload, or drowsiness (Lohani et al., 2019). At the same time, Michels et al., in a scoping review, demonstrate that excessive and non-actionable alerts cause alarm fatigue (desensitization and reduced readiness to respond), which supports the need for signal prioritization, human-centered alerting, and alternative modalities where continuous audible warnings do not increase safety but instead degrade it (Michels et al., 2025).

A second body of sources links safety to digitalization, predictive control, and reliability engineering. Jardine, Lin, and Banjevic, in a review of machinery diagnostics and prognostics for condition-based maintenance (CBM), show how sensor-driven degradation detection enables earlier interventions and reduces unexpected failures that can trigger incidents in heavy equipment and freight operations (Jardine et al., 2006). Moubray's reliability-centered maintenance (RCM) provides a consequence-focused logic for selecting maintenance activities aimed at protecting critical functions (not merely components), while Smith and Hinchcliffe outline practical steps for implementing RCM within "best practice" maintenance programs (Moubray, 1997; Smith & Hinchcliffe, 2004). At the system level, Lee, Bagheri, and Kao propose a cyber-physical systems architecture for Industry 4.0 that links sensing, analytics, and control loops - relevant to viewing safety as a managed engineering process in a "smart" environment (Lee et al., 2015); Borgia reviews the IoT vision, highlighting key features and open issues (interoperability, scalability, security) that directly affect the dependability of sensor-based safety solutions (Borgia, 2014). Rasheed, San, and Kvamsdal analyze digital twins as model-based cyber-physical assets, describing their value for prediction and decision support as well as challenges related to data integration and model fidelity (Rasheed et al., 2019). For proximity safety and flow separation, Al-Hadhrami et al. discuss UWB positioning as a promising high-accuracy localization technology (Al-Hadhrami et al., 2014), and Ochoa-de-Eribe-Landaberea et al. demonstrate a UWB-RTLS concept applied to worker safety zoning (Ochoa-de-Eribe-Landaberea et al., 2024). For vehicle "situational awareness," Qian et al. summarize multi-sensor fusion methods that improve perception robustness (Qian et al., 2025); Colella and Awad trace the evolution of ADAS functions that prevent incidents by assisting or intervening in driving tasks (Shaout et al., 2011); and Dey et al. assess V2V/V2I communications, supporting safety applications where connectivity extends hazard awareness beyond line-of-sight (Dey et al., 2016). Finally, Manzoor et al. show how BIM approaches and digital workflows strengthen safety planning and hazard control in construction (Manzoor et al., 2025), while Żuchowicz and Lewczuk apply immersive technologies to evaluate and train safer forklift operations - useful for modeling near-miss scenarios and validating infrastructure controls before deployment (Żuchowicz & Lewczuk, 2025).

## Problem Statement

Industrial logistics and heavy freight transport operations at critical infrastructure facilities remain exposed to collisions, near-miss events, and sudden equipment failures because safety is still often managed through reactive, compliance-driven measures (signage, briefings, and post-incident investigation). In high-density environments with limited visibility, intersecting trajectories of machines and personnel, high kinetic energy, and operator cognitive overload, these measures do not reliably prevent hazardous scenarios. Although modern technologies exist - smart infrastructure sensing, onboard driver assistance, connectivity, and predictive diagnostics - they are frequently implemented as isolated tools rather than as a single coordinated safety mechanism. The unresolved research problem is the absence of an integrated engineering logic that synchronizes infrastructure controls, vehicle intelligence, and predictive reliability into a deterministic, auditable process capable of preventing incidents rather than merely reducing their consequences.

The main research objective is to develop and justify an integrated deterministic safety methodology ("Chuikov's Multi-Contour Safety System") that transforms safety from a probabilistic outcome into a controlled engineering process for industrial transport systems.

To achieve this objective, the study solves the following tasks:

1. Identify the key limitations of reactive and purely administrative safety models in industrial transport environments and define prevention-oriented system requirements.
2. Develop an interaction algorithm that links smart infrastructure measures (proximity detection, enforced flow separation, access interlocks) with onboard vehicle assistance functions.

3. Substantiate a human-factors warning strategy that reduces alarm fatigue by prioritizing actionable alerts and using alternative feedback channels (including haptic cues) in high-noise conditions.
4. Integrate predictive diagnostics and condition-based maintenance logic to detect degradation early and prevent functional failures that can escalate into incidents.
5. Evaluate the operational effectiveness of the integrated methodology using retrospective evidence and near-miss dynamics as performance indicators.

## Methods and Materials

The relevance of the presented research is dictated by the systemic crisis of traditional transportation safety models, which are reaching their efficiency limits amidst the Fourth Industrial Revolution (Industry 4.0). The exponential growth in the intensity of logistical flows and the increasing kinematic complexity of industrial facilities necessitate a transition from administrative regulation to engineering determinism (Lee, Bagheri, & Kao, 2015).

The methodological foundation of the work is based on the principles of systems engineering and a cybernetic approach to risk management, where the object of protection is viewed as a complex “human - machine - infrastructure” sociotechnical system. Comparative analysis of safety architectures was selected as the key research method - ranging from passive barrier systems to integrated digital ecosystems [9]. The selection of data and technological solutions was conducted based on the criterion of their ability to transform safety from a probabilistic variable into a controlled process. In particular, when analyzing the interaction between operator and machinery, a cognitive ergonomics approach was applied to investigate the phenomenon of “alarm fatigue” - the desensitization of personnel to constant auditory stimuli. This allowed justifying the necessity of transitioning to intuitive visual interfaces (HMI) and tactile feedback channels (Michels et al., 2025; Lohani et al., 2019).

The scientific novelty of the work lies in the synthesis of disparate engineering disciplines from mechanics to Data Science into a unified concept of echeloned defense. For the first time, the necessity of considering safety as a dynamic function implemented through Digital Twin technologies and prescriptive analytics, capable of detecting anomalies via unsupervised machine learning methods before parameters exceed permissible limits, is substantiated (Rasheed et al., 2019).

The investigation of technical operational aspects relied on reliability theory and non-destructive testing methods. To evaluate the effectiveness of predictive strategies, the P-F interval model was utilized, allowing for the identification of the correlation between latent degradation parameters (vibration, tribological composition of oils) and functional equipment failures (Moubray, 1997). The methodology also included an analysis of the operating principles of Sensor Fusion and V2X systems as instruments for expanding the machinery’s “situational awareness” beyond physical visibility. Special attention was paid to the study of Failure Reporting, Analysis and Corrective Action Systems (FRACAS), which allowed assessing the impact of operational data on the constructive evolution of machines (Smith & Hinchcliffe, 2004).

The empirical basis of the research rests on a 15-year retrospective analysis of the system’s operation. The proposed multi-level protection architecture was developed and successfully implemented by the author at a large-scale critical infrastructure enterprise. The study covers a fleet of 350 units of specialized heavy machinery. The efficiency criterion was the dynamics of reducing “near-miss” incidents (potentially dangerous proximities) following the deployment of Chuikov’s Stanislav algorithmic solutions. However, this study has several limitations that must be taken into account when interpreting the results. The work focuses predominantly on the technical and technological side of the issue, leaving aside the economic analysis of costs for implementing the described systems, which may vary significantly depending on the region and the scale of the enterprise. Furthermore, the research does not examine the legal aspects of liability, when decisions are made by artificial intelligence in critical situations, nor the problems of compatibility of the newest digital solutions with legacy equipment, which requires separate study. Nevertheless, the proposed methodological approach allows forming a universal technical map of solutions for minimizing technogenic risks at the current stage of transport engineering development.

## Results and Discussion

### Accident and incident prevention systems in engineering infrastructure facilities: technical solutions and case studies

Ensuring safety within engineering infrastructure facilities, such as industrial sites, logistics hubs or warehouse complexes, can no longer be reduced exclusively to administrative regulation. In practice, the primary source of risk in such environments is the non-linearity of transport flows. When the trajectories of heavy machinery, maneuvering operations and personnel pedestrian routes intersect within a confined space, an inevitable conflict arises. Under conditions of high operational intensity, traditional markings and warning signs rapidly lose their effectiveness. This occurs due to the “sensory blindness” effect, where personnel simply cease to notice habitual stimuli. Consequently, modern engineering thought is shifting towards the forced segregation of flows and the implementation of systems that physically prevent the commission of an error.

Competent zoning remains the foundational level of protection. Where previously this was limited to simple markings, today the standard is becoming the installation of energy-absorbing polymer barriers capable of withstanding the impact of a forklift without the destruction of anchor fastenings or damage to the floor. However, the true breakthrough has been the introduction of active detection systems (Active Detection Systems). Stationary LIDAR and radar complexes, integrated into intersection “blind” spots, operate where human attention may fail (Al-Hadhrami et al., 2014). Upon detecting approaching machinery, such a system projects a visual warning directly onto the floor or even blocks automatic gates, physically cutting off the pedestrian from the hazardous zone until the vehicle has passed. This shifts safety from the domain of the human factor to the domain of reliable automation.

The effectiveness of such an engineering approach is clearly demonstrated by real-world enterprise modernization cases. Illustrative is the experience of a large Class A logistics terminal, where, under conditions of intensive cross-docking, the safety issue in picking zones was acute. Reach trucks and order pickers were constantly in dangerous proximity to one another. The solution was the implementation of UWB (Ultra-WideBand) technology (see Figure 1. A basic scheme of dynamic space zoning). The warehouse was equipped with a network of anchors for positioning and the machinery and employee vests with active tags. A dual safety contour was configured - when objects approached within 5 meters, the forklift automatically slowed to “creep speed” (creep speed) and at a distance of 2 meters it stopped completely. The result of the first year of operation was a 95% reduction in “machine-human” type incidents without a loss in the terminal’s overall throughput capacity (Al-Hadhrami et al., 2014).

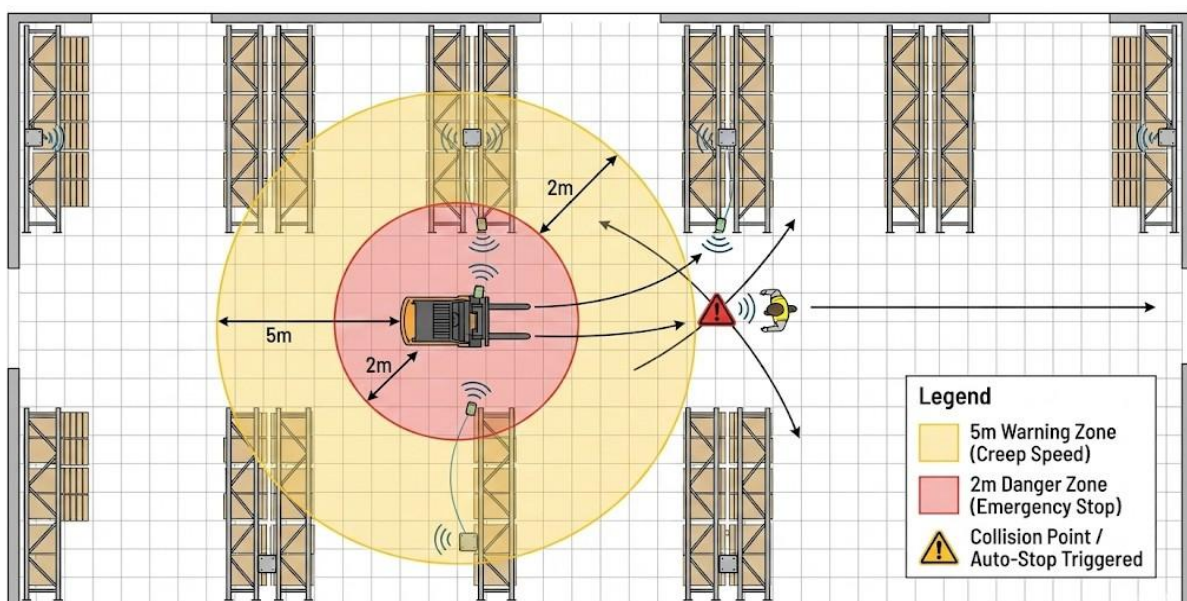


Figure 1. A basic scheme of dynamic space zoning based on UWB (Ultra-WideBand) technology

Another example pertains to the critical loading/unloading zone within automotive manufacturing. Here, a classic problem is the premature departure of the truck from the dock while the forklift is still inside the trailer. To eliminate the risk of equipment falling, the enterprise implemented automated vehicle restraint systems. A specialized mechanism integrated into the dock engages the trailer's rear impact guard or locks the wheel, making vehicle movement physically impossible until operations are concluded. The system is strictly synchronized with the door automation and dock leveler: the forklift simply cannot enter the trailer until the truck is secured. This solution eliminated the risk of severe accidents in this area.

Such examples confirm that modern safety systems are evolving from passive barriers to intelligent ecosystems. In modern realities, infrastructure becomes an active participant in the process, capable of correcting human and machine behavior, thereby preventing accident scenarios at the physical level.

Particular attention within this topic is warranted by the problem of so-called "alarm fatigue". In a saturated production environment, where reversing alarms, horns and sirens sound continuously, the operator's brain begins to filter these sounds as background noise. The engineering response to this challenge lies within the realm of cognitive ergonomics - a transition from auditory stimuli to intuitive visualization. Modern safety systems (for example, BlueSpot or Red Zone projection spotlights) do not require cognitive signal processing - they create a visual barrier directly in the path of movement. This operates at the level of reflexes rather than conscious perception, which is critically important in stressful situations or during night shifts, when personnel's reaction times are diminished.

To address this challenge, the author developed and integrated a specific solution based on cognitive ergonomics - a transition from auditory stimuli to haptic feedback. Within the framework of "The Chuikov's Multi-Contour Safety System", the author proposed replacing constant audio alarms with vibration signals (seat or steering wheel vibration). This approach bypasses the auditory filter of a fatigued operator. Implementation of this specific author's protocol at the test facility resulted in a significant reduction in human error, confirming that tactile channels are more reliable in high-stress environments.

### **Technical approaches to enhancing operational safety in heavy-duty trucks and specialized machinery**

While infrastructure solutions establish a safe environment, the safety of the vehicle itself relies on the machine's capability to compensate for operator errors and maintain physical motion parameters within a permissible range. In modern heavy-duty machinery engineering, a fundamental paradigm shift has occurred: from passive protection designed to minimize impact consequences to active assistance systems (ADAS - Advanced Driver Assistance Systems), the objective of which is to prevent the incident itself (Qian et al., 2025). A freight truck or unit of specialized machinery is viewed today as an intelligent partner possessing its own "situational awareness". While individual ADAS components exist on the market, Stanislav Chuikov developed a unique integration algorithm that synchronizes these vehicle systems with external infrastructure sensors. This ensures that the vehicle acts as an intelligent agent within the unified safety contour.

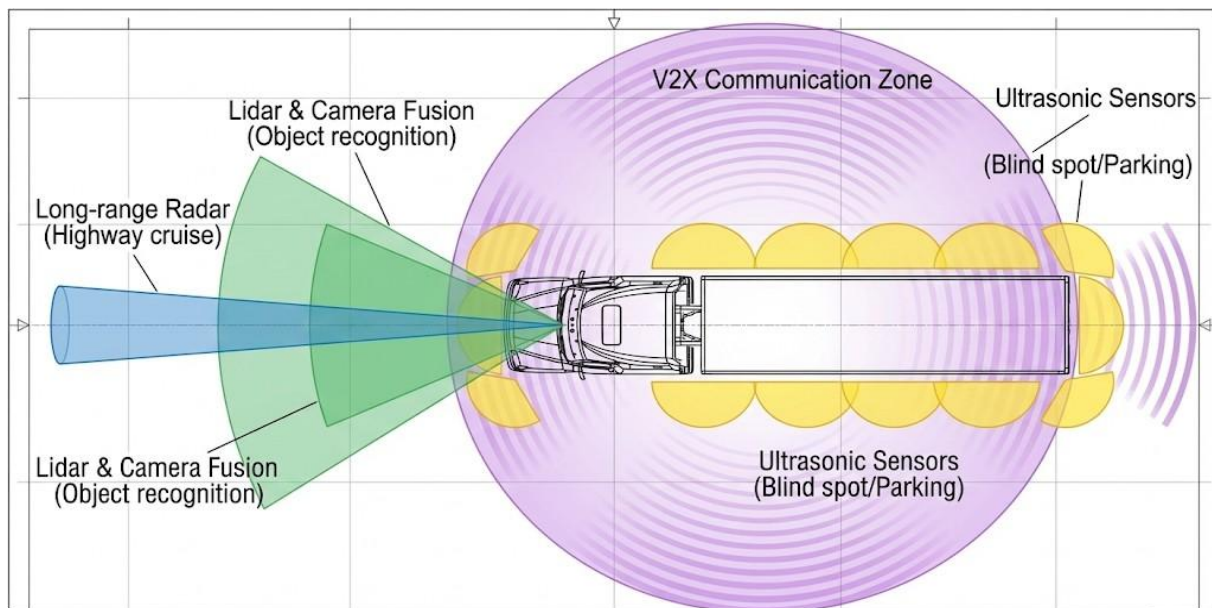
A key challenge in the operation of heavy transport is dynamic stability control. A high center of gravity and cargo inertia render such vehicles prone to rollover or jackknifing. The engineering response to this is the implementation of electronic stability systems (ESC/RSS - Roll Stability Support). Unlike the driver, who reacts to a skid post-factum, these systems operate on preventive measures.

By analyzing data from yaw rate and lateral acceleration sensors hundreds of times per second, the electronics selectively brake individual wheels, returning the vehicle to its trajectory even before the human realizes the loss of control. For specialized construction machinery, the analogue is load moment indicators, which block operator actions in real time if boom outreach or load weight threaten to compromise the machine's static balance.

The next critical aspect is overcoming human sensory limitations. "Blind spots" around large-scale machinery have historically been the primary cause of collisions with personnel and light vehicles.

Modernized solutions are moving away from simple mirrors towards Sensor Fusion technology - the aggregation of data from 360° Surround View cameras and millimeter-wave radars [16]. Computer vision algorithms classify objects, identifying Vulnerable Road Users (VRU). If a person is detected in the risk zone, the system issues an audible signal and a tactile warning (seat or steering wheel vibration) and, in a critical situation, activates autonomous emergency braking (AEB), physically preventing the driver from continuing movement (Shaout et al., 2011).

However, sensors have physical line-of-sight limitations and therefore modern engineering is implementing V2X (Vehicle-to-Everything) technologies, which extend the electronic safety horizon beyond the range of radars (see Figure 2. Diagram of the Sensor fusion architecture and coverage area). By exchanging data with road infrastructure and other vehicles, the truck's onboard computer receives warnings regarding emergency traffic braking kilometers ahead or the approach of specialized machinery from around a "blind" corner (Dey et al., 2016). This transforms safety from an individual characteristic of a single vehicle into a collective resource, where transport vehicles form a unified risk warning network.



**Figure 2. Diagram of the Sensor fusion architecture and coverage area diagram for on-board heavy goods vehicle perception systems**

Finally, safety engineering has closely engaged with the psychophysiological state of the operator himself. The monotony of highway movement or routine operations at a quarry lead to a reduction in vigilance. Driver Monitoring Systems (DMS), utilizing infrared cameras with eye tracking, have become a mandatory safety standard. They detect signs of microsleep, distraction or fatigue based on blink patterns and gaze direction. This closes the safety contour: the machine safeguards the human not only from the external environment, but also from his own physiology, transforming from a tool into an active "co-pilot".

In parallel with driver state monitoring, data transmission interfaces (HMI) are evolving. Engineers are solving the task of minimizing cognitive load: the driver of specialized machinery must not be distracted by reading the dashboard at a critical moment. The solution becomes the use of Head-Up Displays (HUD) and elements of Augmented Reality (AR), which overlay navigational prompts and hazard warnings directly onto the windshield.

This sounds like the future, but already today it allows retaining focus of attention on the road, combining visual control of the environment with the perception of important telemetry.

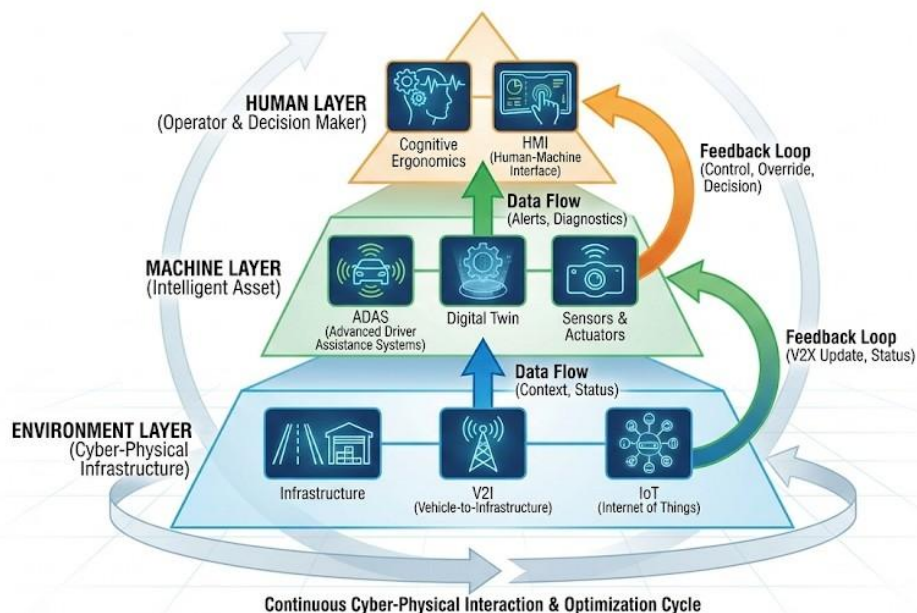
**The role of engineering controls and predictive diagnostics in equipment failure prevention**

The final element of the safety triad is the strategy of predictive reliability. In engineering, equipment failure is viewed not as a sudden event, but rather as the terminal point of a prolonged degradation process that can and must be monitored. The role of engineering control transforms here - instead

of rigid adherence to calendar-based maintenance schedules (Time-Based Maintenance), enterprises are transitioning to “in the moment” Condition-Based Maintenance (CBM). This becomes possible through the deep integration of the Industrial Internet of Things (IoT), transforming every machine component into a source of continuous operational performance indicators.

The technical core of this system is predictive diagnostics, operating at the early stages of the so-called P-F curve (the interval between potential and functional failure). Spectral vibration analysis allows for the detection of micro-cracks in bearings or shaft imbalance hundreds of engine hours before they manifest as noise or overheating. In parallel, real-time tribodiagnostics (oil analysis) detects the presence of metal shavings or lubricant dilution, signaling wear in the cylinder-piston group at the molecular level. Engineering control acts here as a high-precision seismograph, capturing the “tremors” of mechanisms invisible to the human eye (see Figure 4. Conceptual diagram of the P-F curve).

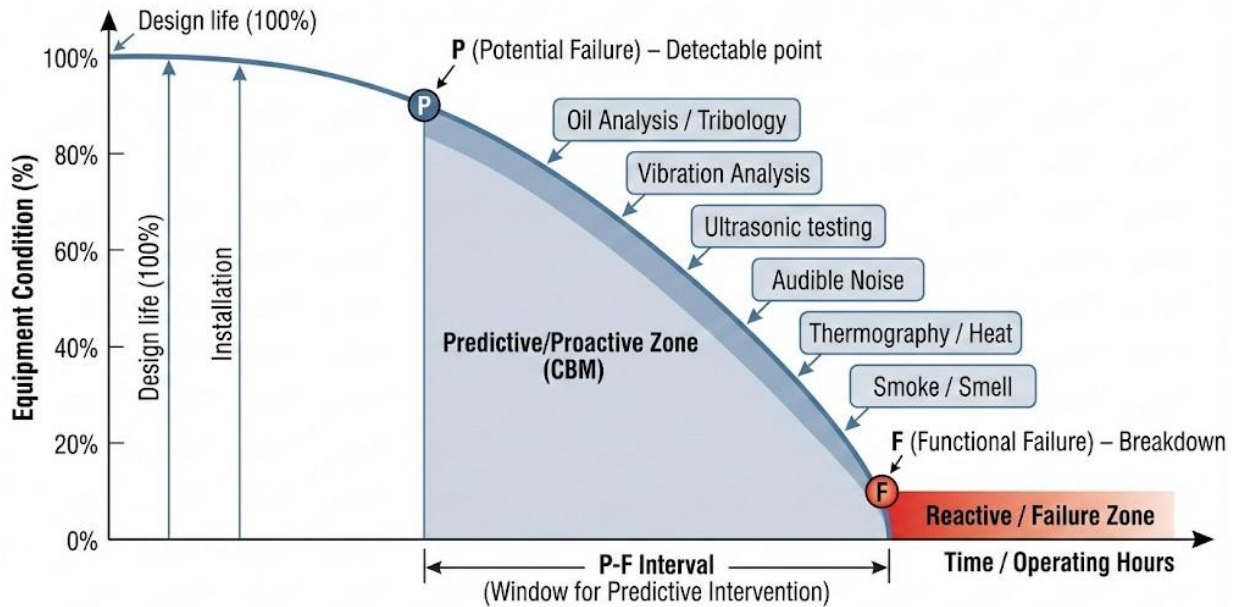
It is important to note, that traditional automation reacts only when a parameter exceeds a “red line” threshold. Intelligent systems utilizing unsupervised learning methods, however, are capable of identifying non-obvious anomalies within permissible ranges. For instance, if the gearbox temperature is formally within the “green zone”, but its rate of increase does not correlate with the current engine load, the neural network recognizes this pattern as pre-emergency. This allows for the detection of hidden assembly defects or fatigue changes that remain invisible to the deterministic logic of legacy controllers.



**Figure 3. Conceptual architecture of cyber-physical security system “Man - Machine – Environment”**

At the apex of this pyramid lie “Digital Twin” technologies (see Figure 3. Conceptual architecture of cyber-physical security system). By creating a virtual replica of a physical aggregate, engineers can model its behavior under current loads, predicting the Remaining Useful Life (RUL) with mathematical precision, as well as projecting, with a detailed study, all possible breakdown scenarios and their rectification. This allows algorithms to advance to prescriptive analytics - the system itself suggests the optimal service window, minimizing downtime. It is a phenomenal development that significantly increases the safety percentage for humans and machinery.

The engineering approach to safety does not end with the rectification of a specific breakdown. A critically important element is the implementation of the FRACAS system (Failure Reporting, Analysis and Corrective Action System). This is a feedback mechanism, where predictive diagnostic data is transmitted to machinery developers. Root Cause Analysis based on Big Data allows engineers to implement constructive changes in subsequent generations of machines, eliminating the equipment’s “genetic diseases”.



**Figure 4. Conceptual diagram of the P-F curve (interval between potential and functional failure) in the context of the maintenance strategy as it stands (CBM)**

In addition, modern engineering control incorporates automated equipment protection protocols (engine protection derate). If the onboard computer detects a critical deviation, it does not await operator reaction, but forcibly activates the power limitation mode (“limp mode”) or completely stops the engine. This is a rigid engineering barrier that physically prevents operating the machinery in emergency mode, saving expensive components from fatal destruction and preventing technogenic risks associated with sudden loss of control.

**Table 1. Comparative analysis of safety paradigms: traditional approaches vs industry 4.0 engineering strategies**

Comparison criterion	Traditional approach (reactive model)	Modern engineering approach (deterministic model)
Philosophy of safety	Compliance-based: focus on rules and administrative penalties. Accident is treated as probabilistic	Risk-based engineering: focus on physical prevention. Accident is treated as a deterministic system failure
Infrastructure control	Passive: floor markings, static signs, mirrors. Relies on human visual attention	Active: UWB zoning, automated barriers, dynamic projection. Relies on physical segregation of flows
Vehicle safety	Mechanical: passive protection (bumpers), mirrors. Driver is the sole decision-maker	Cyber-physical: ADAS, Sensor fusion, V2X. The vehicle acts as an intelligent “co-pilot” with intervention capability
Maintenance strategy	Time-based (TBM): scheduled service regardless of actual condition. High risk of “unexpected” failure	Condition-Based (CBM) + predictive: real-time monitoring (IoT), P-F interval analysis. Zero unexpected downtime
Human factor management	Disciplinary: training and punishment for errors. High “alarm fatigue”	Cognitive ergonomics: intuitive HMI, tactile feedback, vibration. System compensates for human error

### Conclusion

**A**nalysis of the 15-year operational data confirms, that real resilience is achieved only through the deep integration of the three levels of protection proposed in “The Chuikov’s Multi-Contour Safety System”. The author’s specific contribution lies in the development of the logic that binds smart infrastructure, the AI-assisted vehicle and predictive diagnostics into a single organism.

Summarizing the research findings, it can be stated with certainty: the epoch, when transport safety was ensured exclusively by administrative pressure, briefings and “paper” control has irrevocably passed. In the conditions of modern logistics, where speeds are increasing and processes are densified to the limit, human reaction ceases to be a reliable guarantor. A fundamental shift in the

engineering paradigm is observed, because safety has transformed from a set of restrictive rules into a complex cyber-physical architecture. Now this is an intrinsic function of the system itself, a kind of digital immunity of the enterprise, which operates continuously and autonomously.

Analysis of technical solutions shows that real resilience to accidents is achieved only with deep integration of the three levels of protection. The first level is smart infrastructure. It has been demonstrated how warehouse complexes and factories are transforming from passive sceneries into active participants of the process: owing to LIDAR and UWB systems, the environment itself separates flows of people and machines, forcibly stopping equipment where the operator might commit an error due to fatigue or “sensory blindness”. The second level is the evolution of the machine itself. Freight transport has ceased to be simply a mechanism. Stemming from Sensor Fusion and V2X technologies, it has acquired “situational awareness”, the ability to see threats beyond the horizon and, what is critically important, to compensate for the cognitive load on the driver by filtering superfluous informational noise and retaining only important signals. No fewer revolutionary changes have occurred in approaches to machinery reliability. The transition to Condition-Based Maintenance and the implementation of Digital Twins have allowed peering inside the physical processes of degradation. Now, engineers do not read tea leaves awaiting a breakdown, but see the machine’s “disease” in its embryo - be it bearing micro-vibrations or a change in oil chemistry. Moreover, attributable to FRACAS systems and Big Data analysis, operation has begun to directly influence design: failure data forms the “genetic memory” of the industry, allowing the creation of subsequent generations of machines already without the congenital diseases of previous models.

Therefore, the main conclusion is that for critical infrastructure facilities, where safety is a matter of strategic importance, the transition to this deterministic model is mandatory. The author’s system transforms the concept of “zero injury” from a theoretical slogan into an achievable engineering standard.

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