

ASPICE-Based Unified Process Improvement Framework for ISO 26262 Functional Safety Compliance in Automotive Systems

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Abstract: The rapid evolution of automotive electronics, autonomous driving technologies, electrification, and software-defined vehicle architectures has significantly increased the complexity of automotive embedded systems. This transformation has intensified the need for robust process governance, safety assurance, and systematic engineering practices capable of addressing stringent regulatory and quality requirements. Automotive SPICE (ASPICE) and ISO 26262 have emerged as two dominant frameworks within the automotive industry. ASPICE primarily focuses on process capability assessment and software process improvement, whereas ISO 26262 emphasizes functional safety lifecycle management for electrical and electronic systems in road vehicles. Despite their widespread adoption, organizations frequently encounter substantial implementation challenges due to overlapping activities, duplicated documentation, fragmented workflows, inconsistent traceability, and increased compliance costs resulting from independent implementation of both standards. This research proposes an ASPICE-based Unified Process Improvement Framework (UPIF) for achieving efficient ISO 26262 functional safety compliance in automotive systems. The proposed framework integrates ASPICE process areas with ISO 26262 safety lifecycle activities through a harmonized systems engineering approach. The study systematically analyzes existing literature, industrial practices, safety engineering methodologies, and process capability models to identify integration gaps and develop a structured unified model. The framework establishes process alignment among system engineering, software engineering, hardware engineering, verification and validation, risk management, configuration management, and safety assurance activities. The research further evaluates the proposed framework using comparative analysis involving traditional separated implementation models and integrated process architectures. The results demonstrate that the unified framework significantly improves traceability, process consistency, development efficiency, audit readiness, defect prevention, and safety evidence management. Additionally, the framework supports agile and model-based development practices while preserving compliance integrity. The study contributes both theoretically and practically to automotive process engineering by introducing a scalable integration methodology suitable for advanced driver assistance systems (ADAS), autonomous vehicles, electric vehicle platforms, and safety-critical embedded systems. The findings indicate that organizations adopting integrated ASPICE-ISO 26262 process architectures can reduce process redundancy, improve safety culture, accelerate product releases, and enhance overall software and system quality. The proposed framework therefore provides a strategic foundation for next-generation automotive development ecosystems where functional safety, cybersecurity, software quality, and continuous process improvement must coexist seamlessly.

Keywords: ASPICE, ISO 26262, Functional Safety, Automotive Systems, Process Improvement, Automotive Software Engineering, Safety Lifecycle, Unified Framework, Safety Compliance, Embedded Systems.

1. Introduction

The automotive industry has experienced a revolutionary transformation over the past decade due to the rapid emergence of software-intensive technologies such as autonomous driving systems, advanced driver assistance systems (ADAS), electrification, connected vehicles, over-the-air software updates, and artificial intelligence-enabled functionalities. Modern vehicles now incorporate millions of lines of software code distributed across numerous electronic control units (ECUs), sensors, actuators, communication buses, and cloud-connected services. Consequently, the reliability, safety, and quality of automotive embedded systems have become critical concerns for manufacturers, suppliers, regulatory agencies, and consumers alike. Historically, automotive engineering primarily focused on mechanical reliability and hardware robustness. However, the growing dependence on software-defined functionalities has shifted the industry toward systems engineering and functional safety assurance. Failures within software-controlled automotive systems may lead not only to financial losses but also to catastrophic consequences involving human injury and fatalities. Several high-profile incidents involving unintended acceleration, braking failures, sensor malfunctions, and autonomous driving anomalies have reinforced the necessity for rigorous safety-oriented development frameworks.

To address these concerns, the automotive industry adopted ISO 26262 as the international standard for functional safety of electrical and electronic systems in road vehicles. ISO 26262 provides a comprehensive safety lifecycle covering hazard analysis, risk assessment, safety goals, safety requirements, architectural design, implementation, verification, validation, and production support activities. The standard introduces Automotive Safety Integrity Levels (ASILs) to classify safety-critical functions based on risk severity, exposure, and controllability. ISO 26262 establishes systematic approaches for reducing risks

associated with malfunctioning automotive systems and ensuring acceptable levels of residual risk. Simultaneously, Automotive SPICE (ASPICE) has become the de facto industry standard for assessing and improving software development process capability within automotive organizations. ASPICE focuses on process maturity, traceability, project management, quality assurance, systems engineering, software engineering, and support process effectiveness. Original equipment manufacturers (OEMs) increasingly require suppliers to achieve ASPICE capability levels to demonstrate process robustness and development consistency. ASPICE has therefore evolved into a central process governance mechanism within automotive software development ecosystems.

Although both ASPICE and ISO 26262 address quality and safety concerns, their practical implementation within organizations often occurs independently. This separation creates significant inefficiencies including duplicated work products, inconsistent terminology, redundant reviews, fragmented traceability chains, conflicting process artifacts, and increased audit complexity. Engineering teams frequently struggle to maintain synchronization between ASPICE assessment expectations and ISO 26262 safety lifecycle deliverables. As automotive systems become increasingly complex, the need for integrated process architectures capable of harmonizing these standards has become critically important. Recent industrial studies have highlighted the growing demand for unified frameworks integrating ASPICE process areas with ISO 26262 functional safety requirements. Research demonstrates that misalignment between process improvement activities and safety engineering practices can lead to schedule overruns, increased compliance costs, and reduced development efficiency. Despite these concerns, existing research remains fragmented and lacks a comprehensive process integration model capable of systematically aligning ASPICE and ISO 26262 within a unified engineering ecosystem. The present study addresses this research gap by proposing an ASPICE-Based Unified Process Improvement Framework for ISO 26262 Functional Safety Compliance in Automotive Systems. The proposed framework seeks to establish a harmonized development model integrating process capability improvement with functional safety assurance across the automotive product lifecycle. The framework emphasizes end-to-end traceability, process alignment, integrated verification strategies, safety-oriented systems engineering, and continuous process optimization.

The primary objectives of this research are:

- To analyze the relationship between ASPICE process areas and ISO 26262 safety lifecycle requirements.
- To identify integration challenges and process redundancies within current automotive development practices.
- To develop a unified process improvement framework integrating ASPICE and ISO 26262 activities.
- To evaluate the effectiveness of the proposed framework through comparative process analysis.
- To provide implementation guidelines suitable for modern automotive software ecosystems.

The significance of this research lies in its ability to support automotive organizations in simultaneously achieving high process capability and functional safety compliance while minimizing operational inefficiencies. The proposed framework contributes toward establishing a sustainable engineering culture where safety, quality, and process excellence are treated as integrated organizational objectives rather than isolated compliance activities.

2. Literature Review

The convergence of software engineering, systems engineering, and functional safety within the automotive domain has generated extensive academic and industrial research over the past decade. This section critically reviews existing literature related to ASPICE, ISO 26262, functional safety engineering, process improvement models, and unified integration approaches.

2.1. Evolution of Functional Safety in Automotive Systems

Functional safety emerged as a specialized engineering discipline following the increasing reliance on electronic control systems in safety-critical applications. ISO 26262 evolved from IEC 61508 and introduced automotive-specific adaptations addressing vehicle operational contexts, lifecycle management, and risk classification mechanisms. The standard defines a complete safety lifecycle spanning concept development, system design, hardware and software implementation, production, operation, and decommissioning.

Researchers have emphasized that ISO 26262 significantly improved systematic safety engineering practices by introducing hazard analysis and risk assessment (HARA), ASIL decomposition, safety goals, and safety case development methodologies. Hommes (2012) argued that ISO 26262 represented a major advancement over previous generic safety standards by emphasizing early-stage hazard elimination and system-level engineering integration.

Subsequent studies expanded functional safety research toward autonomous driving systems, machine learning integration, fault tolerance, and uncertainty management. Salay et al. examined the challenges of integrating machine learning technologies within ISO 26262 frameworks and identified significant limitations in current safety assurance methodologies for AI-driven systems. Similarly, Mohan et al. proposed systematic architectural methods for developing functionally safe automated driving systems under uncertain design conditions.

These studies collectively indicate that traditional safety engineering methods alone are insufficient for managing the complexity of emerging automotive architectures. Consequently, integrated engineering approaches incorporating process management, traceability, and continuous improvement have become increasingly necessary.

2.2. ASPICE and Automotive Process Improvement

Automotive SPICE was developed to improve software development capability and process maturity within automotive organizations. ASPICE extends ISO/IEC 15504 principles and defines structured process reference models (PRMs) and process assessment models (PAMs) tailored for automotive engineering environments.

ASPICE encompasses multiple process categories including:

- System engineering (SYS)
- Software engineering (SWE)
- Project management (MAN)
- Support processes (SUP)
- Process improvement (PIM)
- Hardware engineering (HWE)

Research indicates that ASPICE significantly enhances traceability, requirement consistency, project predictability, defect management, and development discipline. However, organizations frequently perceive ASPICE implementation as documentation-intensive and bureaucratic when poorly integrated into engineering workflows.

Lingras and Basu proposed modernization strategies for ASPICE-based development environments by integrating agile methodologies, automation technologies, and continuous integration pipelines. Their findings demonstrated that ASPICE and agile practices are not inherently contradictory and can coexist through adaptive process tailoring.

Nevertheless, ASPICE primarily focuses on process quality rather than safety assurance. While traceability and verification support safety engineering indirectly, ASPICE alone does not provide sufficient guidance for hazard mitigation, ASIL management, or safety validation activities required under ISO 26262.

2.3. Challenges in Integrating ASPICE and ISO 26262

The simultaneous adoption of ASPICE and ISO 26262 has become common among automotive OEMs and Tier-1 suppliers. However, multiple studies identify substantial integration difficulties arising from differences in terminology, lifecycle structures, assessment methods, and documentation expectations.

Industrial reports indicate that organizations often maintain parallel workflows for process assessments and safety compliance activities, resulting in duplicated work products and increased engineering overhead. Safety engineers and process quality teams frequently operate independently, creating organizational silos that hinder collaborative systems engineering practices.

Key integration challenges identified in literature include:

- Redundant documentation generation
- Fragmented traceability management
- Misaligned verification strategies
- Inconsistent configuration management
- Duplicate review and audit activities
- Disconnected safety and quality assurance workflows
- Lack of unified metrics for process and safety performance

Several organizations have attempted partial alignment strategies by mapping ASPICE base practices to ISO 26262 work products. However, these mappings often remain superficial and fail to establish operational integration across the complete development lifecycle.

Recent SAE publications proposed refined V-model architectures integrating ASPICE system engineering processes with ISO 26262 safety lifecycle activities. These studies demonstrate promising directions but still lack comprehensive organizational process governance models capable of supporting continuous process improvement and scalable implementation across large automotive programs.

2.4. Systems Engineering and Safety Assurance

Systems engineering plays a central role in both ASPICE and ISO 26262. Effective systems engineering enables requirement decomposition, interface definition, architectural consistency, verification planning, and traceability management across hardware and software domains.

Researchers increasingly advocate model-based systems engineering (MBSE) approaches to address automotive system complexity. Safety-driven development methodologies integrate safety requirements directly into architectural models, enabling early-stage validation and automated consistency checking.

Furthermore, the transition toward software-defined vehicles has expanded the importance of integrated lifecycle management. Safety assurance must now consider cybersecurity threats, cloud connectivity, artificial intelligence behavior, and continuous software deployment mechanisms. Traditional sequential development approaches therefore require modernization toward adaptive, integrated engineering ecosystems.

2.5. Research Gap Identification

The literature review reveals several important research gaps:

- Existing studies primarily focus on conceptual mappings between ASPICE and ISO 26262 rather than operational integration frameworks.
- Limited research addresses organizational process governance mechanisms for unified implementation.
- Few studies provide detailed methodologies for integrating safety lifecycle activities into ASPICE capability improvement processes.
- Existing frameworks often neglect agile development compatibility and continuous integration environments.
- There is insufficient research evaluating process efficiency improvements achieved through integrated frameworks.
- Most available industrial studies remain proprietary and lack publicly accessible implementation methodologies.

The present research addresses these gaps by proposing a comprehensive ASPICE-based Unified Process Improvement Framework integrating functional safety compliance, process capability improvement, and systems engineering alignment within a scalable automotive development architecture.

3. Research Methodology

This study adopts a qualitative and conceptual research methodology combining systematic literature analysis, standards analysis, comparative process mapping, and framework development techniques. The methodology was designed to investigate the integration challenges between ASPICE and ISO 26262 and develop a practical unified process improvement framework suitable for automotive organizations.

3.1. Research Design

The research follows a multi-phase design consisting of:

- Literature exploration
- Standards analysis
- Process mapping
- Gap identification
- Framework development
- Comparative evaluation

The study primarily utilizes secondary data obtained from academic journals, SAE technical papers, ISO publications, ASPICE process assessment documentation, industrial reports, and systems engineering literature.

3.2. Data Collection

Data sources included:

- Peer-reviewed journal articles
- SAE technical publications
- ISO 26262 documentation
- ASPICE process reference models
- Automotive systems engineering studies
- Functional safety research papers
- Industrial case studies
- Process improvement reports

The literature selection criteria focused on:

- Relevance to automotive systems engineering
- Functional safety integration
- ASPICE implementation
- Safety lifecycle management
- Process improvement methodologies
- Automotive software quality assurance

3.3. Comparative Standards Analysis

A comparative analysis was conducted between ASPICE process areas and ISO 26262 lifecycle activities. The analysis focused on identifying:

- Overlapping activities
- Redundant work products
- Common traceability requirements
- Shared verification practices
- Risk management alignment opportunities
- Safety assurance integration points

The following ASPICE process groups were examined:

- SYS (System Engineering)
- SWE (Software Engineering)
- MAN (Management)
- SUP (Support Processes)
- HWE (Hardware Engineering)

Similarly, the following ISO 26262 lifecycle areas were analyzed:

- Concept phase
- System-level development
- Hardware development
- Software development
- Production and operation
- Supporting processes
- Safety management

3.4. Framework Development Approach

The Unified Process Improvement Framework was developed using systems engineering principles and layered process integration concepts. The framework architecture was designed around the following principles:

- End-to-end traceability
- Lifecycle synchronization
- Unified documentation management
- Integrated verification and validation
- Continuous safety assurance
- Process capability optimization
- Compliance automation support

The framework incorporates both process-centric and safety-centric perspectives to ensure balanced integration.

3.5. Evaluation Criteria

The proposed framework was evaluated against traditional separated implementation approaches using the following criteria:

Table 1: Comparative Performance Evaluation of Traditional and Unified Frameworks

Evaluation Parameter	Traditional Approach	Unified Framework
Traceability Efficiency	Moderate	High
Documentation Redundancy	High	Low
Audit Readiness	Moderate	High
Process Synchronization	Low	High
Safety Evidence Consistency	Moderate	High
Development Efficiency	Moderate	High
Rework Reduction	Low	High

Agile Compatibility	Limited	Enhanced
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3.6. Research Validity

To enhance validity, the study triangulated information across multiple sources including academic literature, industrial reports, technical standards, and real-world automotive engineering practices. The proposed framework was further validated conceptually against existing process integration challenges documented in literature.

4. Results and Discussion

4.1. Overview of the Proposed Unified Framework

The proposed ASPICE-Based Unified Process Improvement Framework (UPIF) establishes an integrated engineering architecture aligning ASPICE capability processes with ISO 26262 functional safety lifecycle activities. The framework introduces a harmonized process ecosystem where safety engineering becomes an embedded component of organizational process management rather than an isolated compliance function.

The framework consists of five integrated layers:

- Governance and Safety Management Layer
- Systems Engineering Integration Layer
- Development and Verification Layer
- Traceability and Configuration Management Layer
- Continuous Improvement and Assessment Layer

These layers collectively create a closed-loop process architecture enabling continuous synchronization between safety requirements, engineering activities, and process capability improvement initiatives.

4.2. Governance and Safety Management Integration

One of the major findings of this research is that organizational governance plays a critical role in successful ASPICE and ISO 26262 integration. In many automotive organizations, process quality teams and functional safety teams operate independently, resulting in duplicated oversight mechanisms and fragmented accountability structures.

The proposed framework integrates governance functions by establishing unified management processes incorporating:

- Safety planning
- Project management
- Risk management
- Supplier management
- Configuration management
- Quality assurance
- Compliance monitoring

This integration significantly improves decision consistency and reduces management overhead. The framework also introduces centralized safety governance boards responsible for coordinating ASPICE assessments and ISO 26262 compliance reviews simultaneously.

The integration aligns closely with ISO 26262 Part 2 safety management requirements while leveraging ASPICE MAN process capabilities for project governance and process monitoring.

4.3. Systems Engineering Alignment

Systems engineering emerged as the most critical integration domain between ASPICE and ISO 26262. The research identified that both frameworks rely heavily on hierarchical requirement decomposition, architectural consistency, and traceability management.

The unified framework synchronizes the following activities:

Table 2: Unified Integration of ASPICE and ISO 26262 Process Activities

ASPICE Process Area	ISO 26262 Lifecycle Activity	Unified Integration
SYS.1 Requirements Elicitation	Item Definition	Integrated stakeholder analysis
SYS.2 System Requirements	Functional Safety Requirements	Unified requirement repository
SYS.3 System Architecture	Technical Safety Concept	Safety-aware architecture design
SYS.4 System Integration	Integration Verification	Combined validation planning
SYS.5 System Qualification	Safety Validation	Unified acceptance criteria

This mapping enables organizations to eliminate redundant documentation and establish a single authoritative engineering baseline.

The framework further introduces integrated requirement classification models where functional, safety, cybersecurity, and quality attributes coexist within shared engineering repositories. This approach substantially improves traceability consistency across development phases.

4.4. Integration of Safety Lifecycle Activities

The study found that many organizations struggle with late-stage safety integration, where safety analyses occur independently from mainstream engineering activities. Such approaches often result in architectural redesigns, requirement inconsistencies, and project delays.

The proposed framework addresses this issue by embedding safety lifecycle activities directly into ASPICE engineering workflows. Key integrations include:

- Hazard analysis integrated into requirement elicitation
- Safety goals linked to system architecture
- ASIL allocation synchronized with software decomposition
- Safety mechanisms incorporated into design reviews
- Safety verification embedded into test management systems

This integration transforms safety engineering from a reactive compliance activity into a proactive development discipline.

4.5. Unified Verification and Validation Strategy

Verification and validation (V&V) represent one of the most resource-intensive areas within automotive development. Traditional separated approaches often maintain independent testing strategies for ASPICE compliance and ISO 26262 safety verification.

The proposed framework establishes a unified V&V architecture integrating:

- Requirement-based testing
- Safety requirement verification
- Structural coverage analysis
- Fault injection testing
- Integration testing
- Regression testing
- Safety validation testing

The framework also supports automated traceability between:

- Safety goals
- Technical safety requirements
- Software requirements
- Test cases
- Verification evidence
- Safety cases

This integration substantially improves audit readiness and reduces manual traceability maintenance efforts.

4.6. Traceability Enhancement

Traceability emerged as a central theme throughout the research. Both ASPICE and ISO 26262 require extensive bidirectional traceability across lifecycle artifacts. However, organizations often maintain fragmented traceability chains using disconnected tools and repositories.

The unified framework introduces centralized lifecycle traceability management enabling continuous linkage among:

- Stakeholder requirements
- Safety goals
- Functional requirements
- Technical requirements
- Software components
- Test artifacts
- Safety analyses

- Verification reports

Enhanced traceability provides several benefits:

- Faster impact analysis
- Improved change management
- Reduced defect propagation
- Stronger compliance evidence
- More effective root cause analysis

Additionally, integrated traceability supports continuous compliance monitoring within agile and DevOps-oriented automotive environments.

4.7. Agile and Continuous Development Compatibility

One important finding from contemporary literature is that ASPICE and ISO 26262 are increasingly being adapted to agile automotive development models.

The proposed framework incorporates agile-compatible mechanisms including:

- Incremental safety analysis
- Sprint-level safety reviews
- Continuous integration testing
- Automated compliance checks
- Incremental safety case evolution

This capability is particularly important for software-defined vehicles where continuous software deployment and rapid feature iteration are becoming industry norms.

The framework also supports model-based development and simulation-driven validation approaches commonly used in ADAS and autonomous driving systems.

4.8. Process Capability Improvement

The research indicates that unified process architectures significantly enhance organizational process maturity by reducing fragmentation and improving engineering consistency.

The framework supports continuous improvement through:

- Process performance metrics
- Defect trend analysis
- Safety incident monitoring
- Assessment feedback integration
- Lessons learned repositories
- Continuous process optimization cycles

Organizations implementing integrated frameworks can therefore achieve higher ASPICE capability levels while simultaneously strengthening functional safety compliance.

4.9. Comparative Analysis

The comparative evaluation revealed substantial advantages of the proposed framework over traditional separated implementation approaches.

4.10. Key Improvements Identified

Table 3: Comparative Performance Evaluation of the Traditional Model and Unified Framework

Performance Indicator	Traditional Model	Unified Framework
Documentation Duplication	High	Low
Safety Review Efficiency	Moderate	High
Traceability Maintenance Effort	High	Moderate
Audit Preparation Time	High	Reduced
Defect Detection Efficiency	Moderate	Improved
Change Impact Analysis	Fragmented	Centralized
Safety Evidence Consistency	Variable	Standardized
Agile Adaptability	Limited	Enhanced

The results demonstrate that integrated frameworks provide both operational and compliance-related benefits.

4.11. Industrial Implications

The proposed framework has significant implications for:

- Automotive OEMs
- Tier-1 suppliers
- Embedded software vendors
- Safety engineering teams
- Process quality organizations
- Regulatory compliance departments

The framework is particularly relevant for organizations developing:

- ADAS platforms
- Autonomous driving systems
- Electric vehicle control systems
- Brake-by-wire systems
- Steering control systems
- Battery management systems
- Connected vehicle architectures

As automotive systems continue evolving toward higher autonomy and connectivity, integrated process governance will become increasingly essential.

5. Discussion of Research Contributions

This research contributes to automotive engineering literature in several important ways.

5.1. Theoretical Contributions

- Development of a unified ASPICE-ISO 26262 integration model
- Extension of systems engineering-based process harmonization concepts
- Introduction of integrated safety-process governance mechanisms
- Enhancement of lifecycle synchronization methodologies

5.2. Practical Contributions

- Reduction of process redundancy
- Improved compliance efficiency
- Enhanced traceability architectures
- Agile-compatible safety integration
- Streamlined audit readiness

The framework also establishes a foundation for future integration with cybersecurity standards such as ISO/SAE 21434.

6. Conclusion

The increasing complexity of automotive embedded systems has fundamentally transformed the engineering challenges associated with software quality, systems integration, and functional safety assurance. Automotive organizations are now required to simultaneously satisfy stringent process capability expectations and comprehensive safety compliance obligations while maintaining development efficiency and innovation agility. This research investigated the integration challenges associated with ASPICE and ISO 26262 implementation within automotive development environments. The study identified significant inefficiencies resulting from isolated implementation strategies, including duplicated documentation, fragmented traceability, disconnected verification activities, inconsistent governance structures, and elevated compliance costs. To address these challenges, the study proposed an ASPICE-Based Unified Process Improvement Framework integrating process capability management with ISO 26262 functional safety lifecycle activities. The framework establishes a harmonized engineering architecture encompassing governance integration, systems engineering synchronization, unified verification strategies, centralized traceability management, and continuous process improvement mechanisms.

The findings demonstrate that integrated process architectures provide substantial operational and compliance advantages over traditional separated approaches. The framework improves traceability consistency, reduces engineering redundancy, enhances safety evidence management, supports agile development environments, and strengthens organizational safety

culture. Moreover, the framework contributes to the broader transition toward software-defined vehicles and safety-critical intelligent transportation systems by enabling scalable and adaptive engineering ecosystems. The proposed model therefore represents a valuable strategic approach for automotive organizations seeking sustainable alignment between quality engineering and functional safety assurance. The study ultimately concludes that successful future automotive development will increasingly depend on integrated lifecycle governance models capable of unifying safety, quality, systems engineering, and continuous process improvement within a single operational framework.

7. Future Scope

Although the proposed framework addresses major integration challenges between ASPICE and ISO 26262, several opportunities remain for future research and industrial development.

Future studies may focus on:

- Integration of ISO/SAE 21434 cybersecurity engineering into unified frameworks
- AI-driven safety compliance automation
- Model-based safety case generation
- Continuous compliance monitoring using DevOps pipelines
- Digital twin integration for safety validation
- Machine learning-assisted hazard analysis
- Automated traceability analytics
- Safety assurance for autonomous and AI-enabled vehicles
- Cloud-native automotive software lifecycle management
- Quantitative measurement models for integrated process performance

Additionally, empirical industrial validation through real-world automotive case studies would further strengthen the practical applicability of the proposed framework.

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