

Automind: A Fully Embedded Proactive Safety Advisor for Automotive Systems Using Knowledge Graphs and Quantized LLMs

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Abstract

This paper presents *Automind*, an innovative in-vehicle safety advisor designed to operate entirely offline on embedded automotive hardware. Automind integrates automotive knowledge graphs (KGs) with aggressively quantized large language models (LLMs) to provide proactive, context-aware, and explainable safety guidance to drivers. Unlike traditional reactive Advanced Driver Assistance Systems (ADAS), Automind anticipates risks by correlating real-time vehicle telemetry, regulatory constraints, road topology, and environmental conditions. Through a compact streaming KG architecture and a 3-bit quantized LLM optimized for low-latency inference on embedded platforms, Automind achieves sub-300ms advisory latency with a memory footprint under 2GB, meeting ASIL-B safety standards. We demonstrate its necessity and impact through two realistic automotive scenarios, and propose an implementation roadmap, highlighting commercial and safety value across stakeholders.

1. Introduction

ADAS systems have significantly improved road safety by detecting immediate threats and issuing alerts. However, they are inherently reactive, with limited contextual awareness. These limitations are increasingly evident in complex driving environments, where contextual data such as road geometry, weather, vehicle health, and traffic rules must be holistically evaluated to ensure driver safety.

Automind introduces a next-generation approach, integrating structured knowledge (via knowledge graphs) with natural language capabilities (via LLMs). Running entirely on embedded automotive units, Automind offers proactive, explainable, and privacy-preserving safety guidance that extends beyond the capabilities of conventional ADAS and cloud-based assistants.

2. Motivation: Why Knowledge Graph + LLM?

Neither traditional ADAS nor LLM-only assistants are sufficient for advanced safety reasoning:

- **ADAS** is limited to sensor thresholds and lacks semantic reasoning.
- **LLMs alone** can generate human-like explanations but are prone to hallucinations and lack domain-specific grounding.

Automind leverages KGs for precise reasoning across domains (vehicle health, road rules, environment) and uses a quantized LLM only to articulate guidance in a driver-friendly manner. This hybrid architecture ensures factual integrity, real-time performance, and explainability.

We further address challenges in hallucination mitigation through prompt engineering using KG-derived facts and demonstrate this synergy in high-risk scenarios.

3. System Overview

3.1 Knowledge Graph (KG)

The KG encodes structured relationships:

- **Nodes:** Vehicle components (e.g., brakes, tires), road rules, environment (weather, visibility), road segments.
- **Edges:** e.g., `ROAD_HAS_SPEED_LIMIT`, `BRAKE_HAS_MAX_TEMP`, `WEATHER_AFFECTS_TRACTION`
- **Sources:** NHTSA rules, OSM topology, OEM specifications, weather APIs.

Example Schema Snapshot:

Entity Type	Example	Relationship	Target	Description
RoadSegment	A45_Curve	HAS_SPEED_LIMIT	90 km/h	Legal limit in dry conditions
WeatherCondition	Rain	AFFECTS_TRACTION	-	Reduces stopping performance
BrakePad	OEM_B1	HAS_MAX_TEMP	285°C	Critical overheating point
Tire	AllSeasonX	HAS_TREAD_DEPTH	2.8mm	Influences traction

3.2 Inference Engine

A real-time safety engine implemented in Rust/C streams telemetry and computes risk scores using KG queries and precomputed safety matrices.

3.3 Quantized LLM Advisor

- Model: TinyLlama-1.1B (3-bit quantized)
- Execution: ONNX Runtime + NPU acceleration
- Task: Converts structured advisory data into natural language with KG references

Prompt Engineering Example:

```
{  
  "location": "A45_Curve_Segment_21",  
  "speed": "110 km/h",  
  "brake_temp": "295°C",  
  "weather": "Rain",  
  "tire_tread": "2.8mm",  
  "active_rules": ["HWY-RAIN-5", "BRAKE-MAX-285"]  
}
```

LLM Output:

"Reduce speed to 90 km/h – wet curve ahead and brake temperature approaching critical limit. Tire grip reduced. (Rules: HWY-RAIN-5, BRAKE-MAX-285)"

3.4 Embedded Architecture

- **Minimum Hardware:** Qualcomm SA8155P (4GB RAM, 8 TOPS)
- **Latency:** < 300ms end-to-end
- **Footprint:** < 2GB total (model + KG + logic)
- **Offline Ready:** Supports quarterly OTA KG updates and real-time inference with no cloud dependency.

Additional mechanisms include secure update validation, fail-safe fallback to base regulatory datasets, and KG patch versioning.

4. Use Case Demonstrations

4.1 Use Case 1: Wet Road with Brake Overheat Risk

Context:

- Location: Curved highway segment in rain
- Telemetry: Speed = 110 km/h, Brake Temp = 295°C, Tread Depth = 2.8mm
- Regulation: Max speed in rain = 90 km/h

Traditional ADAS: Would potentially trigger only an overheating alert.

LLM Alone: Might provide generic advice but lacks factual thresholds or weather integration.

Automind Output:

"Reduce speed to 90 km/h – wet curve ahead and brake temperature approaching critical limit. Tire grip reduced. (Rules: HWY-RAIN-5, BRAKE-MAX-285)"

KG Reasoning:

- Speed > Rain_Speed_Limit
- Brake_Temp > Brake_Safe_Threshold
- Tire_Tread < Safe_Minimum => High Stopping Risk

4.2 Use Case 2: School Zone Overspeed in Low Visibility

Context:

- Location: Urban school zone, early morning fog
- Telemetry: Speed = 52 km/h, Visibility < 50m
- Rule: School zone speed limit = 30 km/h (active from 7am)

ADAS: May not account for time-dependent rules or fog impact.

LLM Alone: Cannot detect school zone rules contextually.

Automind Output:

"Slow down to 30 km/h – active school zone with reduced visibility due to fog. Risk to pedestrians increased. (Rule: SCHOOL-ZONE-7AM-30, VISIBILITY-RULE-LOW)"

KG Reasoning:

- Current_Time = 7:45 AM
- Zone_Type = School, Visibility < 60m
- Speed > School_Speed_Limit => High Pedestrian Risk

5. Potential Autonomous Intervention

In high-confidence scenarios, Automind can optionally interface with the vehicle's drive-by-wire system to autonomously enforce safety thresholds. This expands the system from a passive advisory role to an active control layer.

Example:

- KG flags a high-risk combination of wet road, steep curve, and overheating brakes.

- Instead of simply alerting, Automind signals the vehicle control system to reduce speed to the compliant limit.

Benefits:

- Prevents delayed driver response
- Enables consistent safety enforcement
- Reduces false negatives in safety-critical contexts

This optional feature respects regulatory and OEM preferences regarding autonomy and can be toggled per policy or use-case.

6. Technical Feasibility

Automind achieves fully embedded operation through:

- Binary-encoded KG format replacing Neo4j
- Region-specific subgraph extraction
- Streaming query architecture
- 3-bit quantified LLM + prompt caching
- Rust/C-based inference engine with floating-point hardware support
- No cloud dependency except for quarterly updates

7. Dynamic Knowledge Graph Updates

To ensure up-to-date context, Automind shall support:

- **Embedded Navigation Sync:** Interfaces with onboard maps (e.g., HERE, TomTom) to update speed limits, road zones, etc.
- **Offline Patch Delivery:** Quarterly KG updates with region-specific road data delivered via OTA or USB.
- **Real-Time GPS Context Cache:** A lightweight subgraph extracted around vehicle location (<100KB) ensures fast access.
- **Edge Feedback Loop (Optional):** Learns from repeated breaking/accidents to tag high-risk areas over time.

This hybrid approach ensures Automind adapts to evolving traffic regulations and road layouts while preserving offline functionality.

8. Future Work

- Prototype development with CAN bus input
- Expanded regional rules and fault models

- HMI optimization for minimal distraction
- Real-world testing in closed loop simulators and test fleets
- ASIL-B certification process and regulatory collaboration

9. Business Value Proposition

Stakeholder	Value	Metric
Drivers	Contextual, explainable guidance	Reduced accident likelihood
Fleets	Predictive maintenance + compliance	Reduced repair costs
OEMs	Unique embedded safety feature	Monetizable add-on
Insurers	Driver behavior profiling	Usage-based pricing
Regulators	Automated audit logs	Easier compliance verification

10. Implementation Roadmap

Phase	Tasks	Duration
Phase 1	Simulation MVP: KG engine, LLM prompt, UI mockup	4 weeks
Phase 2	Hardware integration, real sensor data, CAN/OBD parsing	8 weeks
Phase 3	Field testing, UI feedback, deployment pilots	12 weeks

11. Conclusion

Automind showcases the transformative potential of combining structured automotive domain knowledge with language intelligence. By operating entirely offline on embedded hardware, it provides real-time, explainable, and proactive safety guidance beyond what current ADAS or AI systems offer. Through use-case driven validation, we highlight its capacity to redefine how vehicles understand and communicate risk.

References

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