AI-Driven Predictive Sonification for Human-on-the-Loop Ground Vehicle Autonomy

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The Human-on-the-Loop Bottleneck

THE SUPERVISORY CHALLENGE

WHY OVERSIGHT IS STILL REQUIRED

- Near-term ground vehicle autonomy still depends on human oversight for safe operation and timely intervention.
- A single supervisor may need to monitor multiple vehicles in teaming configurations.

WHERE VISUAL INTERFACES FALL SHORT

- Telemetry dashboards, alerts, and map products saturate visual attention.
- Subtle, safety-critical trends are recognized late, shrinking the time available to act.

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One supervisor, an entire platoon

EASILY MISSED EARLY TRENDS

- Decreasing inter-vehicle spacing
- Developing control oscillation
- Lane-tracking drift

Less time to detect is less time to prevent a violation and recover stable behavior.

Sound as a Second Channel

WHY SOUND

WHAT SONIFICATION IS

The use of non-speech sound to represent data, so an operator can monitor by ear instead of by eye.

Familiar example: a parking sensor that beeps faster as you approach an obstacle.

WHY A SECOND MODALITY

- Visual attention is already saturated; additional visual alerts compete for the same channel.
- Auditory cues run in parallel, letting supervisors monitor time-varying behavior while keeping eyes on mission and navigation displays.

WHAT THE EVIDENCE SHOWS

- Parameter-mapping sonification and auditory displays suit monitoring without continuous visual fixation.
- Auditory alerting improves event memory and supervisory control of multi-vehicle systems.

DESIGN PRINCIPLES

What effective auditory cueing requires:

- Silent by default
- Encode risk magnitude and trajectory
- Alert before thresholds are violated
- Low-intrusion, never a startle alarm

Background and Contribution

BACKGROUND & POSITIONING

Foundations

- Situation awareness and out-of-the-loop performance frame supervised autonomy.
  Endsley; Kaber and Endsley
- Multimodal interfaces improve awareness and reduce overload in automated vehicles.
  Wang et al.
- Auditory displays and parameter-mapping sonification enable monitoring without visual fixation.
  Nees and Walker; Hermann et al.; Grond and Berger
- Auditory decision aiding improves supervisory control of multi-vehicle systems.
  Donmez et al.

THE GAP

Predictive sonification tailored to human-on-the-loop ground vehicle autonomy remains limited.

OUR CONTRIBUTION

Couple short-horizon forecasting with structured auditory cueing to alert the supervisor before control thresholds are violated, as a modular telemetry overlay that leaves the autonomy stack unchanged.

A Predictive, Risk-Based Auditory Overlay

OUR CONTRIBUTION

1

Forecast-Driven

Short-horizon forecasting of platoon behavior, rather than reaction to the current state alone.

2

Anticipatory

Alerts the supervisor to emerging instability before control thresholds are violated.

3

Magnitude & Trajectory

Conveys how large the risk is and how it is evolving, not a single binary alarm.

4

Modular Overlay

Consumes existing telemetry and requires no modification to the autonomy stack.

From Telemetry to Auditory Cue

SYSTEM ARCHITECTURE

1
Vehicle Telemetry
An interaction state vector is formed at each update step.

2
Forecasting Engine
The current state is propagated forward over a short horizon.

3
Supervisory Trigger
Predicted and active violations combine into a composite risk indicator.

4
Sonification Engine
Composite risk controls when cues fire and how strongly.

5
Auditory Display
Structured cues reach the supervisor without added visual load.

Silent by default. During nominal conditions, the system stays quiet to preserve auditory bandwidth; structured cues activate only when risk thresholds are exceeded.

Forecasting Platoon Behavior

PREDICTIVE MODEL & FORECASTING ENGINE

STATE VECTOR (per update step)

$$x(t) = [\, d(t),\ v(t),\ a(t),\ j(t),\ y(t) \,]^{\top}$$

$d(t)$	Inter-vehicle distance
$v(t)$	Relative velocity
$a(t)$	Longitudinal acceleration
$j(t)$	Jerk
$y(t)$	Lateral deviation

FORECASTING ENGINE

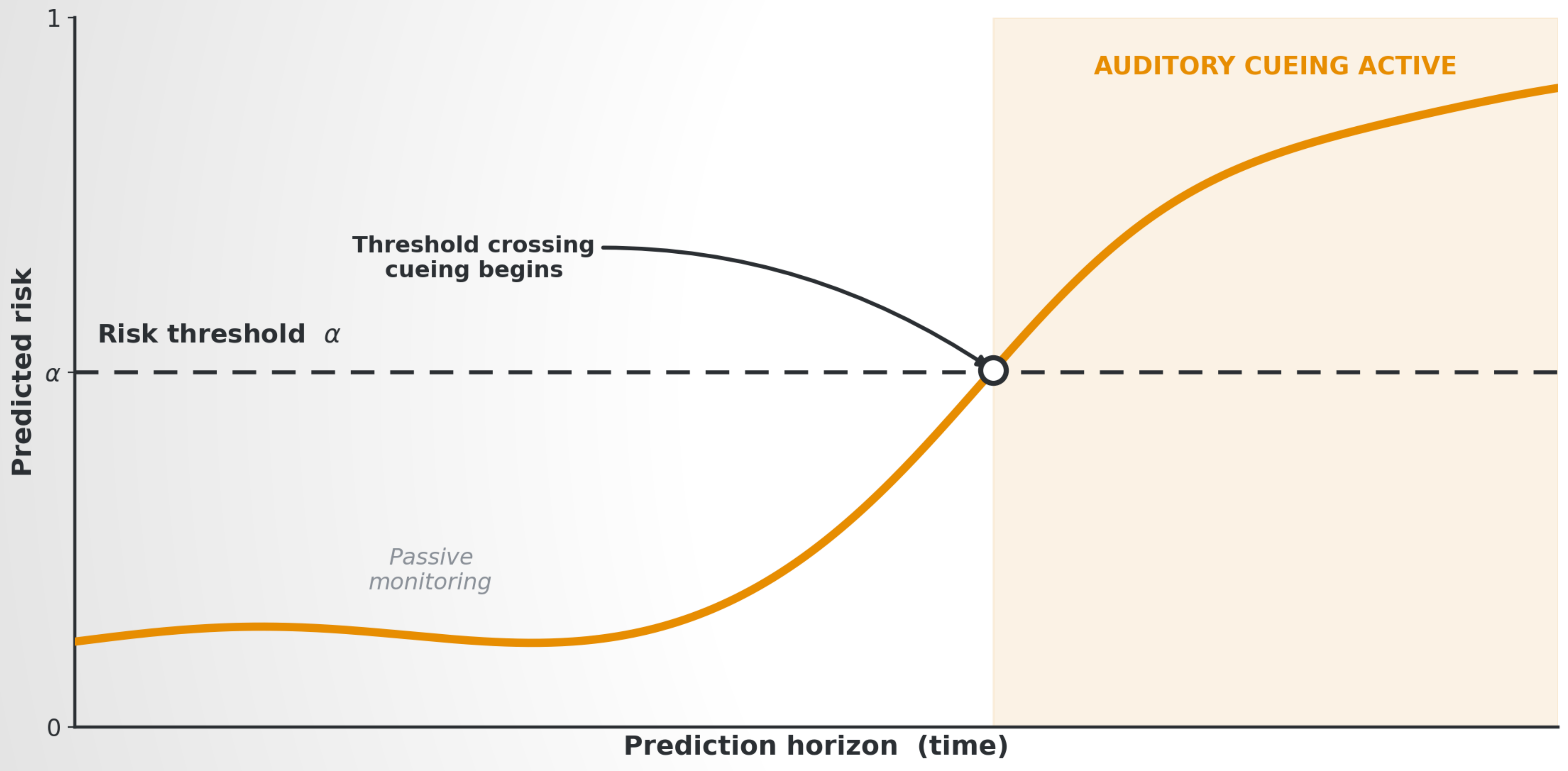
Predict, then evaluate

$$\widehat{x}(t+\tau) = f_{\theta}(x(t))$$

A learned function $f_{\theta}(\cdot)$ propagates the current state over a short horizon τ to a predicted state estimate, supporting detection of unsafe behavior before control thresholds are violated.

Turning Forecasts into a Trigger

RISK ESTIMATION & SUPERVISORY TRIGGER



RISK ESTIMATE

$$r(t+\tau) = g(\widehat{x}(t+\tau))$$

$g(\cdot)$ maps the predicted state $\hat{x}(t+\tau)$ to a normalized risk value $r(t+\tau)$.

ALERT CONDITION

$$\text{Alert} = \begin{cases} 1, & r(t+\tau) \geq \alpha \\ 0, & r(t+\tau) < \alpha \end{cases}$$

Cueing is enabled when predicted risk exceeds a tunable threshold α before an active violation occurs.

Mapping Risk to Sound

SONIFICATION DESIGN FRAMEWORK

INPUT

Predicted & Active Violations

Risk signals from the supervisory trigger.

mapping functions

❯

- **Pitch** — tonal height
- **Loudness** — signal intensity
- **Modulation** — temporal texture
- **Spatial panning** — left-right position

EXAMPLE PARAMETER MAPPING

Inter-vehicle spacing error maps to pitch; cue intensity rises as predicted risk grows.

$$f_{\text{pitch}}(t) = f_0 + k_p\, e_d(t)$$

Three Supervisory States

OPERATIONAL USE CASES

1

Normal Operation

SYSTEM SILENT

Forecast predicts stable behavior with no predicted or active violations. The system stays silent and the supervisor uses standard mission displays.

2

Anomaly

CUES BUILD

The forecast predicts a follower will breach a threshold within the horizon. Low-intrusion cues begin and grow with risk, giving early, intuitive awareness.

3

Intervention

HIGHER URGENCY

An active violation is detected in real time. Output shifts to a higher-urgency profile; the supervisor adjusts platoon behavior, modifies mission parameters, or assumes manual control.

Human-Subject Study Design

PLANNED EXPERIMENTAL EVALUATION

Study Design

- Participants act as platoon supervisors in a simulated four-vehicle convoy.
- Within-subjects, counterbalanced conditions: visual-only and visual plus predictive sonification.
- Scenarios span nominal operation, a developing anomaly, and a control violation requiring response.
- The simulator presents realistic vehicle dynamics, communications delays, and mission tasking.

Metrics

OBJECTIVE MEASURES

- Time to detect predicted violations
- Time to initiate corrective action
- Frequency of missed or late interventions
- Stability recovery time after intervention

SUBJECTIVE & COGNITIVE MEASURES

- NASA-TLX workload
- SART situation awareness
- Usability and trust of the interface

Fielding the Overlay

INTEGRATION PATH FOR GROUND VEHICLE AUTONOMY

HOW IT INTEGRATES

- A modular, non-intrusive overlay that consumes existing telemetry and communication streams, leaving core control unchanged.
- Standardized V2V and V2I interfaces, including DSRC and C-V2X message sets.
- Leverages common data products: vehicle state estimates, health-monitoring signals, and autonomy-supervisor outputs.

WHY IT DROPS IN CLEANLY

- External to the primary autonomy stack, so it suits both legacy and next-generation Army systems.
- Insertable into experimental platforms, technology demonstrators, and test assets without disrupting safety architectures.
- Supports incremental deployment, exercising partial functionality during early integration.

INTEGRATION PATHWAYS

- **Leader-follower convoys**
  Platoon spacing and stability monitoring
- **Autonomous logistics vehicles**
  Sustained route supervision
- **Teleoperated systems**
  Low-visual-burden alerting channel
- **Optionally manned combat vehicles**
  Supervisory oversight when unmanned

Conclusion and Future Work

CONCLUSION & FUTURE WORK

Key result. Coupling short-horizon forecasting with structured auditory cueing enables earlier detection of emerging instability while reducing reliance on visually intensive supervisory interfaces.

Conclusion

- Integrates predictive modeling, threshold-based supervisory logic, and intuitive sonification into a single modular architecture.
- Supports nominal supervision, early anomaly awareness, and time-critical intervention without unnecessary cognitive burden.

Future Work

- Complete the planned human-subject experimental evaluation.
- Integrate the architecture with operational autonomy platforms.
- Explore adaptive mapping, task-dependent cueing, and multi-platform formations.

Q & A

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