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AI-DRIVEN PREDICTIVE SONIFICATION FOR HUMAN-ON-THE-LOOP GROUND VEHICLE AUTONOMY

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ABSTRACT

Ground vehicle autonomy increasingly depends on human-on-the-loop (HOTL) supervision, yet supervisors are often overloaded by visual interfaces that can obscure emerging risks. This paper presents an AI-driven predictive sonification architecture that converts short-horizon forecasts of platoon behavior into structured auditory cues for supervisory monitoring. A forecasting engine predicts future vehicle interaction states and evaluates predicted and active violations to generate a composite risk indicator. When risk exceeds defined thresholds, a sonification module conveys risk magnitude and trajectory through changes in pitch, loudness, modulation, and spatial panning. The paper describes the system architecture, sonification design, operational use cases, and a planned human-subject evaluation. The proposed framework is intended to improve early awareness of emerging instability and support more timely supervisory intervention.

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1. INTRODUCTION

Ground vehicle autonomy is advancing across commercial and defense applications, enabling concepts such as autonomous logistics convoys, robotic combat vehicles, and optionally manned platforms. Despite these advances, near-term deployment still requires HOTL oversight to ensure safe operation and timely intervention when autonomy performance degrades or mission conditions change. In convoy and platoon settings, a single supervisor may be responsible for monitoring multiple vehicles while simultaneously managing mission tasks, communications, and navigation.

A key limitation in current HOTL systems is the visual burden imposed by supervisory interfaces. Telemetry dashboards, alerts, and map products can saturate attention and delay recognition of subtle but safety-critical trends such as decreasing inter-vehicle spacing, developing control oscillations, or lane-tracking drift. Reduced time-to-detect directly reduces the time available to prevent threshold violations and recover stable behavior. Unlike additional visual alerts that compete for already saturated visual attention, auditory displays allow supervisors to monitor time-varying system behavior while maintaining visual focus on mission displays and navigation.

Accordingly, this paper presents an AI-driven predictive sonification architecture that supplements visual interfaces with structured auditory cues representing predicted and active risk states in an autonomous platoon. A forecasting engine predicts short-horizon platoon behavior from vehicle telemetry and evaluates predicted violations using a supervisory risk model. When risk exceeds defined thresholds, a sonification module conveys risk magnitude and trajectory through changes in pitch, loudness, modulation, and spatial panning. The key contribution of this work is a predictive risk-based auditory cueing framework that alerts the human supervisor to emerging instability before control thresholds are violated in real-time. The approach is designed as a modular supervisory overlay that uses existing telemetry data without modifying the autonomy stack. The paper describes the system architecture and operational use cases and outlines a planned human-subject evaluation to measure workload, situation awareness, and intervention timing.

2. LITERATURE REVIEW

Ground vehicle autonomy is progressing from driver-assist features toward supervised autonomy, where human supervisors oversee multiple platforms rather than directly controlling a single vehicle. In this HOTL framework, supervisors must maintain situation awareness over distributed platoons, detect emerging hazards, and determine when and how to intervene, consistent with the situation awareness model described by Endsley [1]. Traditional visual displays and textual alerts can saturate attention and delay detection of subtle but safety-critical changes in system state, a challenge closely related to the out-of-the-loop performance problems described by Kaber and Endsley [2].

Wang et al. [3] reviewed human-machine interfaces for automated vehicles and found that multimodal alerting and feedback mechanisms are critical for maintaining situation awareness and minimizing cognitive overload. Nees and Walker [4] describe auditory displays as a complementary modality for in-vehicle information presentation, making them well suited for monitoring time-varying system behavior without continuous visual fixation. Nees et al. [5] found that speech auditory alerts improved memory for alerted events in a video-simulated self-driving car ride, supporting the use of auditory cueing to improve event detection during automated-vehicle supervision. Hermann et al. [6] describe sonification as the use of non-speech sound to represent data, supporting monitoring tasks in which continuous visual fixation is undesirable. Grond and Berger [7] describe parameter-mapping sonification as the association of information with auditory parameters for the purpose of data display; in this context, system variables can be encoded using pitch, loudness, modulation, and spatial position. Donmez et al. [8] demonstrated that auditory decision aiding can improve supervisory control performance in multi-vehicle unmanned systems; however, predictive sonification tailored to HOTL ground vehicle autonomy remains limited. This work builds on supervisory control and auditory display literature by coupling short-horizon forecasting with structured auditory cueing to provide early awareness of emerging platoon risk states in human-on-the-loop ground vehicle autonomy.

3. SYSTEM ARCHITECTURE OVERVIEW

3.1. Overview of the Predictive Sonification Pipeline

The predictive sonification pipeline, shown in Figure 1, converts raw vehicle telemetry into short-horizon risk estimates and transforms those estimates into an auditory display that supports human-on-the-loop supervision. At each update step, the system operates on a vehicle interaction state vector representing the relative motion and control dynamics of each vehicle in the platoon.

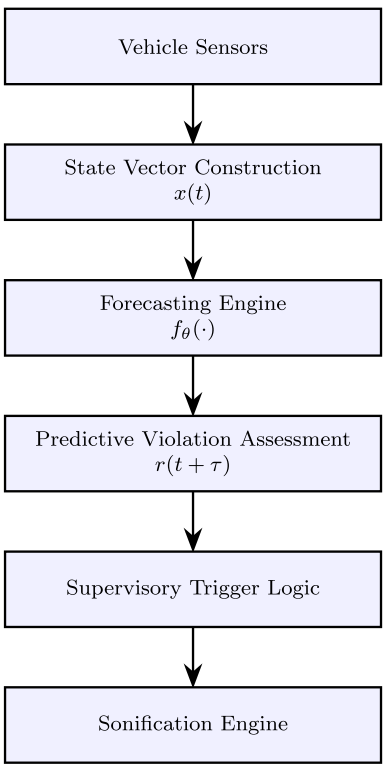

Figure 1: Predictive sonification pipeline illustrating the transformation of vehicle telemetry into predicted risk estimates and supervisory auditory cues.

Rather than redefining the state variables, this stage focuses on how the state is transformed into predictive and supervisory information. A forecasting engine propagates the current state forward over a short horizon, producing predicted system behavior that is evaluated for emerging instability and control risk.

Predicted states are processed by a supervisory trigger framework that evaluates predicted and real-time violations and creates a composite risk indicator. This risk signal serves as the control input to the sonification engine, determining when auditory cues are enabled and how strongly they are expressed.

During nominal conditions, when neither predicted nor active violations are present, the system remains silent to preserve auditory bandwidth. When risk thresholds are exceeded, the system dynamically activates structured auditory cues to support rapid and intuitive supervisory response.

4. PREDICTIVE MODEL AND FORECASTING ENGINE

The predictive modeling component estimates short-horizon future platoon states to enable proactive supervisory cueing. The model operates on a compact vehicle interaction state vector and produces forward predictions over a finite forecasting horizon, supporting early detection of unsafe behavior before control thresholds are violated.

4.1. Model Inputs and State Variables

At each update step, the system creates a vehicle interaction state vector containing the variables most relevant to platoon stability, as defined in Equation (1):

$$x(t) = \begin{bmatrix} d(t) \\ v(t) \\ a(t) \\ j(t) \\ y(t) \end{bmatrix} \quad (1)$$

In Equation (1), $d(t)$ is inter-vehicle distance, $v(t)$ is relative velocity, $a(t)$ is longitudinal acceleration, $j(t)$ is jerk, and $y(t)$ is lateral deviation.

A learned forecasting model then propagates the current state forward over a short prediction horizon to produce a predicted state estimate, as shown in Equation (2):

$$\hat{x}(t+\tau) = f_\theta\big(x(t)\big) \qquad (2)$$

In Equation (2), $f_\theta(\cdot)$ represents a parameterized predictive function and τ denotes the forecast horizon.

4.2. Forecasting Architecture

Predicted states are transformed into a scalar risk estimate that represents the likelihood of future control violations, as defined in Equation (3):

$$r(t+\tau) = g(\hat{x}(t+\tau)) \qquad (3)$$

In Equation (3), $g(\cdot)$ maps the predicted state $\hat{x}(t+\tau)$ to a normalized risk value $r(t+\tau)$. A supervisory alert is then generated by comparing the predicted risk to a tunable threshold, as shown in Equation (4):

$$\text{Alert} = \begin{cases} 1, & r(t+\tau) \geq \alpha \\ 0, & r(t+\tau) < \alpha \end{cases} \qquad (4)$$

In Equation (4), α is the risk threshold used to enable supervisory cueing. Figure 2 illustrates a representative predicted-risk trajectory for a four-vehicle convoy and highlights the interval in which auditory cues are activated when $r(t+\tau) \geq \alpha$. As the predicted risk approaches and then exceeds the threshold, the figure shows how the supervisory logic transitions from passive monitoring to active cueing. When this alert condition is satisfied, the sonification engine is activated and auditory cues are generated to convey both the magnitude and evolution over time of the predicted risk, allowing the supervisor to recognize emerging instability, anticipate potential control degradation, and initiate corrective action before an active threshold violation occurs in real-time.

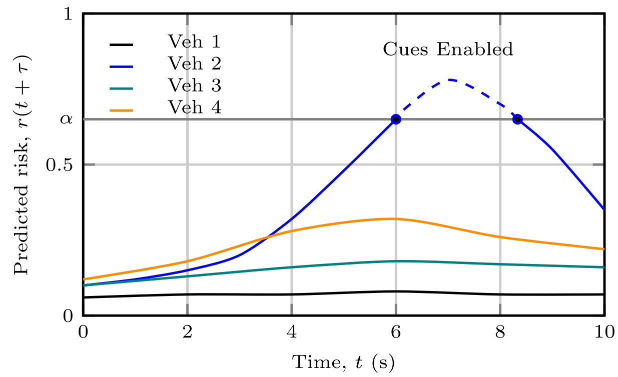

Figure 2: Predicted risk trajectories for a four-vehicle convoy. Auditory cues are enabled when the anomaly vehicle's predicted risk $r(t+\tau)$ exceeds the threshold α (dashed segment).

5. SONIFICATION DESIGN FRAMEWORK ARCHITECTURE

5.1. Sonification Objectives and Design Principles

The sonification subsystem is designed to provide a continuous, low-intrusion auditory representation of predictive risk while preserving the supervisor's primary visual attention for vehicle supervision, teleoperation, and other mission-critical tasks. Unlike traditional alarm-based warning systems that activate only after threshold violations occur, the proposed approach emphasizes anticipatory awareness by encoding both the magnitude and trajectory of predicted risk. Figure 3 illustrates the sonification mapping architecture, showing how active and predicted violations are transformed through mapping functions into auditory parameters including pitch, loudness, modulation, and spatial panning.

6. OPERATIONAL USE CASES

6.1. Normal Operation

Under nominal operating conditions, the forecasting engine predicts stable platoon behavior, and no predicted or active violations are present. In this state, the sonification engine remains silent, preserving auditory bandwidth for radio

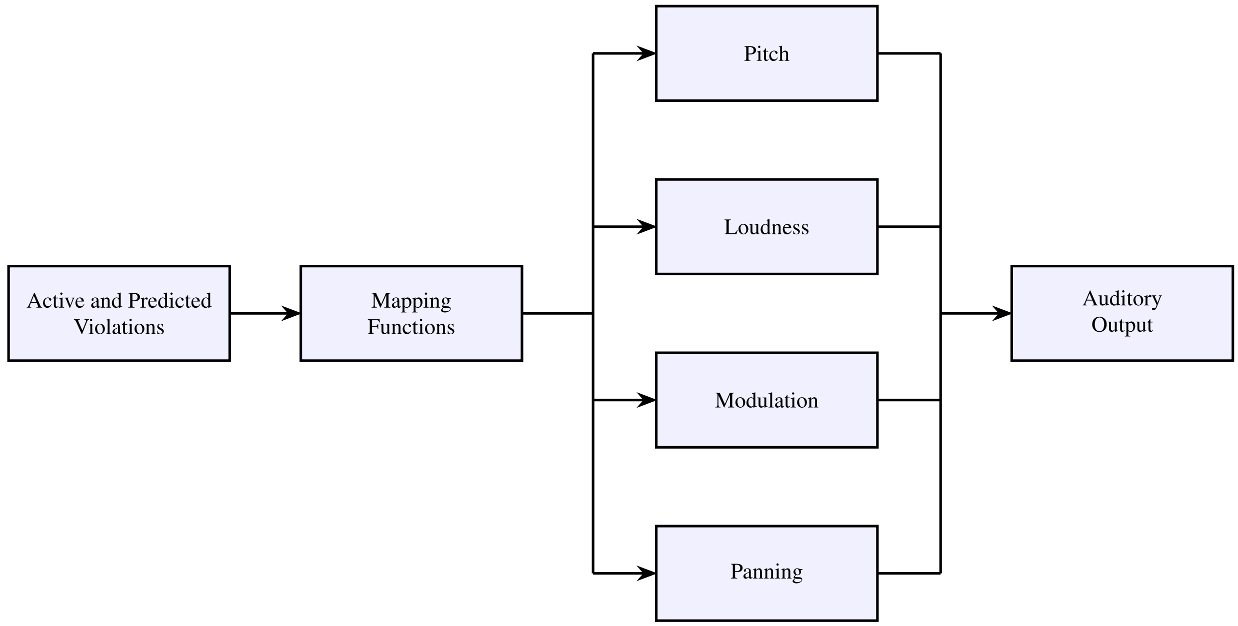

Figure 3: Sonification mapping architecture illustrating how predicted and active violations are transformed through mapping functions into auditory parameters including pitch, loudness, modulation, and spatial panning.

communications and preventing unnecessary cognitive load.

The supervisor monitors the platoon through standard mission displays while the predictive system operates passively in the background. Subtle, non-critical fluctuations in vehicle spacing or velocity are absorbed by the autonomy stack and do not result in auditory output. This silent operating mode is essential to maintaining trust in the system and avoiding desensitization to auditory cues.

6.2. Anomaly Scenario

In an anomaly scenario, the forecasting engine predicts that a follower vehicle will violate a control threshold within the prediction horizon. Typical cases include decreasing inter-vehicle spacing, rising velocity mismatch, or developing oscillatory behavior in the control response.

Before any active violation occurs, the system enables low-intrusion auditory cues. These cues gradually increase in intensity as predicted risk grows, providing the supervisor with early, intuitive awareness of emerging instability. In most cases, this early cueing allows the supervisor to assess the situation and prepare corrective action before safety margins are violated.

The autonomy stack continues to operate during this phase, with the sonification system acting as an anticipatory supervisory interface rather than a hard-warning mechanism.

6.3. Intervention Scenario

In the intervention scenario, a control threshold is exceeded in real-time, and an active violation is detected. The sonification output transitions to a higher urgency acoustic profile, reflecting both the magnitude and persistence of the violation.

At this stage, the supervisor may take one of several actions, including issuing supervisory commands to adjust platoon behavior, modifying mission parameters, or assuming manual control of the lead vehicle if required by mission policy or safety considerations.

The sonification system continues to provide real-time auditory feedback during the intervention, allowing the supervisor to evaluate the effectiveness of corrective actions without relying solely on visual displays. Once stability is restored and no predicted or active violations remain, the system smoothly returns to a silent state.

7. PLANNED EXPERIMENTAL EVALUATION

7.1. Experiment Overview

A controlled, human-subject study is planned to evaluate the operational impact of predictive sonification on human-on-the-loop supervision of ground vehicle autonomy. The study is designed to assess whether structured auditory cueing improves supervisory performance without increasing cognitive workload.

Participants will serve as platoon supervisors in a simulated four-vehicle convoy environment. Each participant will complete a series of supervision scenarios under two counterbalanced conditions: visual-only and visual plus predictive sonification. Scenarios will include nominal operation, developing anomalies, and control violations requiring supervisory response.

The simulator will present realistic vehicle dynamics, communications delays, and mission tasking to approximate operational cognitive demands. Participant actions, system states, and event timelines will be recorded for subsequent analysis.

7.2. Metrics

Performance will be quantified using both objective and subjective measures.

Objective metrics include:

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

Subjective and cognitive metrics include:

- NASA Task Load Index (NASA-TLX) workload scores, as defined by Hart and Staveland [9]
- Self-reported situation awareness ratings using the Situation Awareness Rating Technique (SART) described by Taylor [10]
- Usability and trust ratings for the sonification interface

Comparisons will be made between the two experimental conditions to evaluate whether predictive sonification improves intervention timeliness and reduces supervisory workload without introducing distraction or overreliance.

8. INTEGRATION PATH FOR GROUND VEHICLE AUTONOMY

The proposed predictive sonification architecture is designed to integrate with existing and emerging ground vehicle autonomy frameworks as a modular, non-intrusive supervisory interface. Rather than modifying core vehicle control algorithms, the system operates as an overlay that consumes existing telemetry and communication streams.

Integration can be achieved through standardized vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) interfaces, including dedicated short-range communications (DSRC) and cellular vehicle-to-everything (C-V2X) message sets. The architecture leverages commonly available data products such as vehicle state estimates, health monitoring signals, and autonomy supervisor outputs, minimizing the need for platform-specific software modification.

Because the sonification module is external to the primary autonomy stack, the approach is compatible with both legacy and next-generation Army ground vehicle systems. This enables insertion into experimental platforms, technology demonstrators, and operational test assets without disrupting existing safety architectures.

The approach is also relevant to teleoperated and optionally manned scenarios in which operators cannot maintain continuous visual attention on a supervisory interface. In tactically dynamic environments, predictive sonification can provide a low-visual-burden alerting channel that supports continued autonomous operation while drawing operator attention only when predicted or active violations require intervention.

Potential integration pathways include application within leader-follower convoy architectures, autonomous logistics vehicles, teleoperated systems, and future optionally manned combat vehicle concepts. The framework is intentionally designed to support incremental deployment, allowing partial functionality to be exercised during early integration phases while avoiding mission risk during transition.

9. CONCLUSION AND FUTURE WORK

This paper presented an AI-driven predictive sonification architecture designed to enhance human-on-the-loop supervision of ground vehicle autonomy. By coupling short-horizon forecasting with structured auditory cueing, the system enables earlier detection of emerging instability and reduces reliance on visually intensive supervisory interfaces.

The proposed framework integrates predictive modeling, threshold-based supervisory logic, and intuitive sonification mappings into a modular architecture suitable for ground vehicle autonomy applications. Operational use cases illustrate how the system supports nominal supervision, early anomaly awareness, and time-critical intervention without adding unnecessary cognitive burden.

Ongoing work will focus on completing the planned human-subject experimental evaluation and expanding the architecture toward integration with operational autonomy platforms. Future extensions will examine adaptive mapping strategies, task-dependent cueing, and broader application across multi-platform vehicle formations.

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13. ACRONYMS

GVSC	Ground Vehicle System Center
AI	Artificial Intelligence
C-V2X	Cellular Vehicle-to-Everything
DSRC	Dedicated Short-Range Communications
NASA-TLX	NASA Task Load Index
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle