A Cognitive Approach in In-vehicle Warning Sound Design

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This paper was presented in the Music and Text course as my term project.

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A Human-Centric UX Approach for Sensor Priority and In-Vehicle Warning System Design

Abstract

Modern vehicles—particularly electric and hybrid models—are becoming quieter and more automated, reducing traditional engine-noise cues and increasing reliance on intentionally designed auditory warnings. As Advanced Driver Assistance Systems (ADAS) expand, they generate many alerts that must remain clear and usable within crowded visual interfaces, making it essential for automotive UX design to integrate human-factors principles, regulatory expectations, and sensor behaviors to ensure safe driver interaction. Without a unified structure, however, and especially when this service is outsourced, it becomes increasingly challenging for external companies to conduct the deep technical analysis and cross-functional coordination required with internal ADAS teams. To address these gaps, this work introduces a human-centered computational model that organizes 122 use cases into a coherent auditory-warning ecosystem through structured feature mapping, a six-level urgency taxonomy, functional-unit classification, and a priority-ordering algorithm, ultimately reducing cognitive load and enabling scalable multimodal warning design.

Contents

1 Introduction

In this study, I present a User-Experience (UX)–driven framework for designing, classifying, and prioritizing in-vehicle warning sounds within increasingly automated, electrified, and sensor-intensive mobility systems. As the automotive industry transitions toward quieter electric architectures, long-standing auditory cues are rapidly diminishing, making intentionally crafted auditory communication essential for maintaining safety, situational awareness, and perceptual continuity.

Contemporary Advanced Driver Assistance Systems (ADAS) introduce numerous alerts, each with distinct urgency levels, perceptual demands, and regulatory constraints. Managing these alerts consistently across visually saturated human-machine interfaces presents a significant UX challenge. This work addresses this need through a structured approach integrating human-factors principles, international regulations, and vehicle-sensor behaviors into a unified warning-sound ecosystem.

Section 2 examines auditory display research foundations, safety functions including spatialized warnings and attention redirection, and regulatory frameworks (UNECE, FMVSS) governing warning-sound implementation. Section 3 introduces the computational model organizing 122 OEM-level use cases through structured data architecture, six-level urgency classification (subdividing Warning into High/Middle/Low), eight functional units reflecting system boundaries and driver mental models, and a lexicographic priority algorithm resolving simultaneous warning conflicts. Section 4 translates computational structures into perceptual experiences through color-coded visual hierarchy (red through green), metrical acceleration via loop-rate variations (500–3000 ms), timbre-based functional identification, and spatial audio positioning matching hazard direction. Together, these components enable ADAS teams, UX researchers, and designers to collaborate through unified data architecture, filling a longstanding gap in OEM workflows where no single role oversees global warning-system coherence.

2 Auditory Displays

Auditory displays use sound to convey information, warnings, and system states in human-machine interfaces, translating data into structured acoustic forms that complement or substitute visual channels. In automotive contexts, these systems have evolved from simple warning chimes into sophisticated multimodal communication frameworks that support driver awareness, hazard detection, and system transparency across increasingly automated vehicle platforms. This section examines the research foundations underlying auditory display design, their safety-critical functions in modern vehicles, and the regulatory frameworks that govern their implementation.

2.1 Research Foundations

Auditory display research has expanded considerably over the past two decades, reflecting a growing recognition of sound as a critical communication channel in human–machine interaction (HMI). In the automotive field in particular, the increasing prevalence of electric and hybrid vehicles whose powertrains operate far more quietly than internal combustion engines has fundamentally shifted design priorities to craft meaningful auditory identities and safety-oriented alert systems.

Foundational sonification research has established methodological principles for translating data into structured auditory forms, enabling the development of more consistent and scientifically grounded sound-based representations (Hermann et al., 2011). The integration of sound with visual interfaces has proven highly effective, given the auditory system's superior temporal sensitivity, rapid pattern-recognition abilities, and ability to convey urgency more reliably than visual channels alone. As a result, accessibility, usability, and aesthetic quality now stand alongside functionality as central drivers of sound design practice.

As driving environments become more visually dense—featuring multiple displays, augmented reality interfaces, and increasingly complex traffic scenarios—the importance of auditory displays in vehicles has grown substantially. ADAS and higher levels of automation (SAE J3016) place heavy demands on the visual channel, making sound a particularly valuable modality for communicating safety-critical information. Numerous studies show that auditory alerts significantly reduce driver reaction times compared to visual warnings and can outperform haptic cues in situations involving high visual or cognitive load (Geitner et al., 2019; Kim et al., 2017; Bella & Silvestri, 2017b; Wang et al., 2019; Gray, 2011). In particular, research on collision-warning systems demonstrates that auditory warnings are especially effective when driver attention is diverted from the roadway or instrumentation (Biondi et al., 2016; de Winter et al., 2022).

In partially automated vehicles, auditory alerts have become indispensable for supporting control transitions, directing attention to hazards beyond the automation system's capabilities, and maintaining situational awareness when drivers are engaged in non-driving tasks (Geitner et al., 2019; Pi-Ruano et al., 2024; Yun & Yang, 2020; Nees et al., 2016).

2.2 Safety Functions in Automotive Systems

Because sound propagates omnidirectionally and has inherent attention-capturing properties, auditory cues often outperform visual information channels in urgent situations where milliseconds matter. Experiments conducted in complex urban intersections reveal that spatialized auditory warnings—sounds that convey directional information—enable drivers to orient more rapidly toward the source of danger than visual warnings alone (Bella & Silvestri, 2017). This spatial fidelity is particularly valuable in environments featuring multiple simultaneous threats. Within automated driving systems, auditory cues help mitigate the "out-of-the-loop" phenomenon, in which disengaged drivers struggle to regain awareness after long periods of passive monitoring (Petermeijer et al., 2017; Ho & Spence, 2005).

Carefully designed auditory signals can redirect driver attention even when gaze is misaligned with the threat location, thereby improving hazard recognition and response time. Beyond simple alerting, sonification provides a powerful mechanism for communicating system state, automation level changes, and vehicle intent in continuous, non-intrusive ways. These forms of sound-based communication contribute to trust, transparency, and appropriate mental models of vehicle behavior (Kim et al., 2024; Song et al., 2022; Nadri et al., 2021). By offloading information from overloaded visual channels and distributing it across auditory and haptic modalities, modern auditory displays have become indispensable safety components in increasingly automated vehicle ecosystems. Taken together, these findings underscore the increasingly central role of auditory displays in supporting safe, efficient, and cognitively manageable driving experiences. As I expand this discussion to the broader regulatory landscape, I now turn to the formal standards and legal frameworks that shape how these warning systems must be designed and implemented in modern vehicles.

2.3 Regulations

At this part, I provide an overview of how key regulatory frameworks in the European Union and the United States govern in-vehicle warning sounds across different functional categories. Across both regions, more than a dozen regulatory instruments collectively govern the design, activation logic, and acoustic properties of in-vehicle warning sounds, with specific mandates addressing pedestrian protection, collision avoidance, lane keeping, seatbelt reminders, and broader human–machine interaction requirements. By summarizing which aspects are explicitly mandated and which remain unregulated in each region, Table 1 highlights both common foundations and the design freedoms that shape automotive auditory UX practice.

In the United States, Federal Motor Vehicle Safety Standard (FMVSS) 141 mandates Acoustic Vehicle Alerting Systems (AVAS) for electric and hybrid vehicles traveling below 30 km/h. This regulation specifies minimum sound pressure levels and spectral properties to ensure pedestrian detectability, particularly for individuals with visual impairments. Additional National Highway Traffic Safety Administration (NHTSA) guidelines shape requirements for Forward Collision Warning (FCW), Lane Departure Warning (LDW), and Automatic Emergency Braking (AEB), defining warning timings, intensity patterns, and expected driver responses.

As for the European regulations, it adopts a similarly comprehensive approach. UNECE Regulation No. 138 governs external sound requirements for quiet vehicles, mandating speed-dependent audible signals ranging between 56–75 dB depending on operational mode. Other UNECE regulations—such as No. 130 for lane departure warnings and No. 131 for advanced emergency braking—indirectly influence auditory alert design by prescribing performance expectations that shape alert timing, modality selection, and user-interaction patterns.

Category	**Regulation(s) (EU / US)**	**EU – INCLUDED**	**EU – EXCLUDED**	**US – INCLUDED**	**US – EXCLUDED**
External Pedestrian Warning (EV/Hybrid)	EU: UN R138 (QRTV/AVAS) US: FMVSS 141	AVAS mandatory (56–75 dB)	No tone/melody rules	Mandatory AVAS presence	No sound signature rules
Collision / AEB / FCW	EU: UN R131, UN R152 US: AEB/FCW rule, NCAP protocols	Warning timing / activation criteria	No acoustic pattern specification	AEB/FCW timing performance	No tone/rhythm constraints
Lane Departure Warning (LDW)	EU: UN R130 US: LDW guidance, AEB rule refs.	LDW must issue warning	No freq/rhythm rules	LDW warning required in guidance/tests	No required acoustic form
Seatbelt Reminders	EU: UN R16 US: FMVSS 208	Front/rear SBR with audible warning	No specific tone/timbre	Seatbelt warning required	No sound-design specification
Blind Spot Warning / RCTA	EU: EU GSR 2019/2144 (BSW/RCTA fitment)	System presence required	Sound behavior unregulated	No specific FMVSS for BSW/RCTA	OEM-defined sounds
Driver Monitoring / Drowsiness	EU: EU GSR 2019/2144 (DMS)	DMS alerts to driver required	No audio tone standard	No federal DMS regulation	No acoustic definition
Reversing / Backup Alarms	EU: national rules (work vehicles), no EU-wide car rule US: OSHA, SAE J994	Country-level requirements only	No EU-wide car reversing spec.	Work-vehicle backup alarm required	No FMVSS reversing sound for cars
Turn Signals / Telltales	EU: UN R121 (audible telltales) US: FMVSS 108 (lighting)	Presence of audible telltales	No cadence/pitch rules	Lighting/telltale presence only	Turn-signal sound unregulated
Automated Driving TOR	EU: UN R157 (ALKS) and ADS guidance US: NHTSA HF guidance only	TOR must be clearly communicated (multi-modal)	No unified TOR sound pattern	Only HF recommendations, no binding rule	OEM-defined chimes
General Auditory HMI Standards	EU/US: ISO 7731, ISO 11429, ISO 15006 (referenced standards)	Used as design basis where adopted	Not mandatory for all cases	Used in HF guidance and OEM processes	Not federally required; OEM choice
Non-safety Sounds (branding, UX tones)	– (no direct safety regulation)	No regulation if not safety-related	Free design space	No regulation if not safety-related	OEM / brand-defined

Table 1: Comprehensive EU–US requirements and referenced regulations for in-vehicle warning sounds.

Research on multimodal warning strategies shows that coordinated auditory, visual, and haptic alerts significantly enhance takeover performance in automated driving scenarios, aligning with regulatory objectives that emphasize intuitive and effective human–machine interaction. Both U.S. and European guidelines caution against excessive alerting, underscoring the need to minimize annoyance, reduce false alarms, and ensure perceptual clarity. Poorly designed warnings—overly loud, mismatched in urgency, or confusing in frequency—can lead drivers to disable safety systems entirely, undermining the protective intent of these technologies. Recent studies further demonstrate that multimodal take-over request designs integrating auditory cues, visual indicators, speech messages, and haptic stimulation substantially improve driver responsiveness in conditional automated driving (Yun & Yang, 2020; Hong & Yang, 2022; Yu et al., 2025). As automation progresses, regulations increasingly call for standardized, intelligible, and context-adaptive auditory strategies that support safe interaction across diverse environments, a challenge that directly motivates the UX research and design goals pursued in the present work.

3 UX Research

Beyond regulatory compliance, effective warning-sound design requires balancing perceptual detectability, semantic clarity, and user acceptance within complex organizational structures where multiple ADAS features must coalesce into a unified auditory language. This section addresses the fundamental challenge facing automotive UX researchers: synthesizing fragmented empirical insights into a coherent multimodal ecosystem. It introduces a computational model that systematically organizes 122 use cases through urgency classification, functional-unit categorization, and priority-ordering algorithms, thereby enabling scalable, context-sensitive warning coordination across modern vehicle platforms.

3.1 Design Challenges in ADAS Warning Systems

Effective auditory warnings must balance rapid detectability, clear semantic meaning, and acceptable subjective comfort—grounded in perceptual principles and dynamically adapted to situational demands (Rocchesso et al., 2022; Neidhardt et al., 2022). Sounds that are too subtle may go unnoticed, while overly intense signals can induce startle responses, stress, or long-term annoyance. Yet, because auditory perception and tolerance vary substantially across individuals, even well-designed warnings remain subject to personal preference. Nevertheless, the role of researchers and designers is to interpret and apply industry standards while integrating empirical insights and user-centered considerations, striking a balance essential for preventing cognitive overload and ensuring that drivers respond promptly and accurately to real hazards.

Complementing this perspective, (Wang et al., 2021) highlights how visual design elements that maintain clear semantic consistency and intuitive graphical mappings further enhance users' ability to interpret warnings quickly. Together, these findings reinforce the effectiveness of well-designed auditory icons when integrated within a coherent multimodal interface. In line with these foundational guidelines, two core design questions emerge. First, how can we cultivate a design mindset that ensures a clear semantic relationship between a warning sound, users' preexisting associations, and the safety-related use cases the sound is intended to represent? Second, how should these sounds be integrated with the corresponding visual materials on the dashboard—commonly referred to as telltales in the automotive industry (e.g., the red brake-system warning icon, the yellow lane-departure indicator)—to create a coherent and easily interpretable multimodal message? Before these questions can be meaningfully addressed, however, it is essential to understand how they intersect with the everyday working environment of engineers in automotive OEMs, particularly within ADAS teams, where system specifications, sensor constraints, regulatory requirements, and UX considerations must be continuously integrated into practical design decisions.

Advanced Driver Assistance Systems (ADAS) integrate radar, lidar, camera, and other sensor technologies to enhance safety, comfort, and operational efficiency. These systems continuously process environmental data to identify hazards and automate driving functions such as adaptive cruise control, lane keeping, blind-spot monitoring, and emergency braking. Classified under the SAE levels of automation, where the Society of Automotive Engineers (SAE) defines a six-level framework ranging from Level 0 (no automation) to Level 5 (full autonomy), ADAS technologies represent a foundational stepping stone toward fully autonomous vehicles.

Within automotive development organizations, ADAS teams are typically modular and interdisciplinary, consisting of specialists in sensor engineering, perception algorithms, human–machine interface design, and software integration. Effective collaboration across these teams is essential for aligning hardware, software, and UX considerations. Feature Owners of each or couple of use-cases hold responsibility for the end-to-end development of specific functions, coordinating requirements, system design, implementation, and validation to ensure safety, reliability, and user satisfaction. At this point, a practical challenge emerges in the real working environment: while each Feature Owner is accountable for the development of their individual feature, no single role is inherently responsible for overseeing how all features collectively contribute to a coherent, semantically meaningful in-vehicle warning sound ecosystem. This raises a central question for UX researchers and designers—how can the diverse set of ADAS features be integrated into a unified auditory language that preserves clarity, consistency, and perceptual logic across the entire vehicle?

3.2 Computational Model Overview

UX researchers contribute through surveys, interviews, simulator experiments, and prototype evaluations to understand driver perceptions, cognitive load, and preferences. However, the challenge lies in synthesizing fragmented insights into a coherent design strategy that seamlessly couples with multimodal warning channels. The computational model addresses this through intelligent prioritization, balancing completeness with selectivity.

The model consists of four interconnected components: feature and use case analysis, urgency level classification, functional-unit categorization, and priority ordering algorithms. To display the end result of these components, the dashboard demonstration system developed alongside this research instantiates the computational model through a web-based interface simulating 122 distinct ADAS warning cases. This implementation provides a tangible artifact for UX research and testing, demonstrates prioritization algorithm feasibility, and offers a platform for iterative refinement based on user feedback.

3.3 Features and Use Cases

UX teams must obtain the entire feature list, typically defined by the marketing department according to vehicle segment and product strategy. While hypothetical here yet grounded in automotive industry experience, these features become comprehensive use-case scenarios detailed by Feature Owners in Research&Development (RD) divisions of OEMs with all required specifications for implementation. Rather than approaching warning design through isolated feature definitions, I developed a structured data architecture that captures the relationships among regulatory requirements, system behaviors, and human-factors considerations across 122 real-world automotive use cases. It is essential to bring this structure into alignment with the vehicle's sound ecosystem; in other words, the information architecture built for the feature list must meaningfully interface with the auditory ecosystem of the car to ensure that every sound is grounded in functional logic, system context, and coherent multimodal communication. Thus, these features are the kernel of the data structure organizes warning scenarios through a multi-dimensional taxonomy. In the present work, I encoded them in twelve interconnected fields as Table 2 represents.

Information clustering in the table directly supports the computational processes outlined in the previous section and the lexicon of the information architecture which will be explained later: identification fields establish unique identifiers and priority rankings feeding conflict resolution mechanisms. Functional categorization captures feature names, six-level urgency classifications (Feedback through WarningHigh), and eight functional units, thereby enabling systematic cross-referencing between regulatory requirements and system behaviors. Algorithm parameters provide numeric inputs directly consumed by priority resolution procedures. Implementation specifications link database entries to deployed assets through file references, dashboard messages, and channel definitions specifying multimodal combinations and spatial audio positioning, thus bridging computational decisions with perceptual outcomes.

The outcome of the urgency classification in Functional Categorization maps directly to the urgencyLevelPriority in Algorithm Parameters, while the outcome of the unit-definition process in Functional Categorization maps to the unitPriority field in Algorithm Parameters. Together, these two dimensions determine the casePriority for each uniquely identified feature in the Identification Fields. Finally, as a downstream process, these computational structures are translated into concrete UX artifacts—auditory signals, visual telltales, dashboard messages, and spatialized sound channels—within the Implementation Specifications layer.

Now, I turn to the three core components that structure the prioritization logic: the

Table 2: Data Structure Taxonomy: Field Definitions and Distributions Across 122 Use Cases

Field	Description & Distribution
Identification Fields	
`ID`	Sequential identifier (1–122)
`casePriority`	Global priority ranking (1–122, lower = higher priority)
Functional Categorization	
`featureName`	Descriptive label of ADAS feature or vehicle system
`URGENCY`	Six-level urgency taxonomy: `Feedback` (14), `Notification` (25), `Caution` (21), `WarningLow` (15), `WarningMiddle` (24), `WarningHigh` (23)
`UNIT`	Functional grouping: `HighEmergency` (8), `LowEmergency` (10), `LowSafety` (36), `BrakeSystems` (12), `(ADAS)PrimaryControl` (11), `(ADAS)Road&TrafficSignCases` (28), `(ADAS)Awareness` (7), `Media` (10)
Algorithm Parameters	
`urgencyLevelPriority`	Numeric urgency rank (1–6)
`unitPriority`	Priority ranking within functional unit
Implementation Specifications	
`fileNameIntegration(svg)`	Visual telltale asset filename reference
`fileNameIntegration(wav)`	Audio alert asset filename reference
`dashboardMessage`	Natural language text for dashboard display
`Channels`	Modality and spatial audio specification indicating direction of sound within the cabin (e.g., center, left, right, rear-left, rear-right).

urgency-level priority, the unit-level priority, and, as the combined outcome of these two processes, the overall priority-order determination.

3.3.1 Urgency Level Priority

Urgency level classification translates diverse warning scenarios into a standardized scale guiding auditory design and prioritization decisions. Empirical findings consistently reinforce this relationship: experimental results show that aligning auditory warning urgency with threat severity improves driver reaction time and collision avoidance performance (Wu et al., 2018) and mathematical modeling studies demonstrate that perceived urgency and intuitiveness directly shape takeover behavior in automated driving (Ko et al., 2022). Finally, recent psychoacoustic evaluations further confirm that standardized urgency scales provide an effective foundation for designing graded auditory alerts (Atamer et al., 2025).

The hierarchical urgency framework adopted in this work builds upon foundational principles outlined in "The Sonification Handbook", which characterizes how auditory displays should convey varying degrees of criticality in human–machine systems (Hermann et al., 2011). At the highest level, Warning signals communicate immediate danger and demand rapid user action, reflecting the handbook's description of alarm-class sounds that elicit fast, reflexive responses in critical situations. Caution signals indicate elevated but not yet critical risk, supporting user awareness without provoking panic, consistent with discussions of auditory cues that maintain vigilance in dynamic environments. Notification messages convey system information that does not require immediate intervention, aligning with the handbook's treatment of non-urgent auditory messages common in everyday interfaces. Finally, Feedback sounds provide real-time, continuous responses to user actions, mirroring the handbook's explanations of interactive sonification where sound reinforces system state and user input.

In the present work, I recognize the need to refine the broad Warning category into a more formal sub-categorization that better supports the priority-ordering process. When more than fifty use cases are assigned the same warning-level urgency by Feature Owners, treating them as a uniform class becomes too coarse to manage and lacks the granularity required for precise differentiation. To address this limitation, I subdivide the Warning category into three graded levels—WarningHigh, WarningMiddle, and WarningLow. Although structurally simple, this refinement has proven highly effective in practice, as it introduces meaningful distinctions among scenarios with varying degrees of criticality and greatly simplifies downstream prioritization work. This three-tiered structure ultimately serves as a crucial bridge between high-level urgency classification and the computational mechanisms that determine case-specific priority values. As the end result, the computational model employs a six-level urgency classification scheme: warning High, warning Middle, warning

Low, caution, feedback and notification represented with 122 use cases that reflect increasing levels of threat severity and the corresponding demands placed on the driver.

WarningHigh represents the most critical conditions—situations requiring immediate action with almost no reaction time—such as drowsiness detection or severe tire-pressure loss. WarningMiddle involves events that still require timely driver response but pose less immediate danger, for example the deactivation of one-pedal driving or moderate drowsiness advisories. WarningLow covers lower-severity situations in which the driver should stay attentive and may need to correct a developing issue, such as stability-control notices or attention reminders.

Moving further down the scale, Caution includes advisory messages that raise situational awareness without requiring direct intervention, such as system-status changes or mild tire-pressure fluctuations. Feedback captures continuous system responses that help drivers understand real-time vehicle behavior—for instance, confirmations related to cruise-control availability or charging progress. Finally, Notification encompasses routine informational updates, including attention-monitoring feedback or temperature-related messages.

Overall, the taxonomy progresses from urgent, action-demanding events to low-criticality informational cues, ensuring that each category aligns both with driver expectations and with the practical needs of multimodal warning design.

3.3.2 Priority of Units in the Vehicle

As a second layer in the priority algorithm, while unit priority constitutes an essential component of the overall priority algorithm, in the present work I also propose it as a novel and conceptually useful categorization layer that brings additional structure and interpretability to the warning-system framework. This functional unit taxonomy organizes the 122 use cases into eight coherent categories that reflect both technical system boundaries and the mental models drivers use to interpret vehicle behavior.

The functional units in this framework group use cases by the type of driving task or system function they support. ADAS Awareness focuses on monitoring the driver's internal state, covering drowsiness- and attention-related alerts across several urgency levels. ADAS PrimaryControl addresses core vehicle-control functions, including tire-pressure assessments and cruise-control status changes that help maintain stable operation. BrakeSystems captures braking-related issues, ranging from collision-linked interventions to general system faults.

HighEmergency targets critical failures such as fire detection or high-voltage system faults, while LowEmergency includes more routine but still safety-relevant alerts, for example door-status warnings or temperature irregularities. Road Traffic Sign Cases represents one of the largest groups, covering infrastructure-recognition tasks such as collision risks and lane-keeping deviations. LowSafety, the broadest category, encompasses lower-severity driving situations like parking maneuvers and seatbelt-related messages. Finally, Media includes non-safety functions related to connectivity and voice-interaction feedback.

In this hierarchical ordering—from ADAS Awareness to Media—a minimalist but functionally meaningful rationale emerges. Awareness forms the first priority because driver cognition and attention are prerequisites for safe vehicle operation. Once awareness is secured, maintaining stable primary control becomes the next essential layer, followed by braking capabilities that enable decisive intervention. HighEmergency and LowEmergency functions address acute and moderate hazards, while LowSafety and Media represent everyday operational scenarios that, although important, carry lower immediate safety risk. This structured rationale provides a clear foundation for translating functional categories into priority-ordering logic within the computational model.

3.3.3 Priority Order Algorithm

Figure 1 illustrates how the two priority dimensions—urgency level and unit priority—interact within the vehicle's warning-system hierarchy. As noted earlier, once these formal categories are presented to the Feature Owners, the first step in the workflow is to assign an urgency category to each use case through cross-functional alignment, establishing the foundation for the second phase: determining the unit priority. Critically, urgency level acts lexicographically: a use case with higher urgency always supersedes any lower-urgency case regardless of unit priority. Within each urgency tier, unit priority then determines final ranking.

To illustrate this mechanism, consider a simplified configuration with 24 use cases distributed across two vehicle units, A and B. After cross-functional meetings with Feature Owners from all ADAS teams, the features labeled A–X are assigned urgency levels as shown in Table 4. At this stage, the urgency classification is complete and conceptually coherent, but within each unit the use cases remain "flat" in terms of their relative importance: they share an urgency level but lack a finer-grained ordering. Resolving this requires a second step in which UX researchers hold dedicated workshops with each ADAS team to agree on intra-unit priority, thereby shaping the final case-priority structure exemplified in Table 5.

The priority computation follows lexicographic ordering formalized in Algorithm 1. First, cases are grouped by urgency level (1 = WarningHigh through 6 = Notification). Within each urgency tier, cases are sorted by unit priority, then by intra-unit rank determined through workshop consensus. This yields the final `casePriority` values used for real-time conflict resolution when multiple warnings trigger simultaneously.

Algorithm 1 Priority Order Computation

Require: Set of use cases $C = \{c_1, c_2, \ldots, c_n\}$
Require: Each c_i has: urgencyLevel $\in [1, 6]$, unitID, unitRank
Ensure: Each c_i assigned unique casePriority $\in [1, n]$

Sort C by urgencyLevel (ascending)
$p \leftarrow 1$ ▷ Initialize priority counter
for $u = 1$ to 6 **do** ▷ For each urgency level
  $C_u \leftarrow \{c \in C : c.urgencyLevel = u\}$
  Sort C_u by (unitPriority, unitRank)
  for each $c \in C_u$ **do**
    $c.casePriority \leftarrow p$
    $p \leftarrow p + 1$
  end for
end for

Assuming Unit A is assigned a higher unit priority than Unit B, the initially neutral configuration in Table 4 is transformed into the ordered structure illustrated in Table 5. The same logic generalizes to an arbitrary number of features, urgency levels, and units, making the approach scalable to real OEM-level warning-system architectures.

This section establishes the foundational conditions under which in-vehicle auditory warnings must operate, integrating regulatory requirements, perceptual principles, and engineering constraints. Through cross-functional collaboration with ADAS Feature Owners, it organizes 122 automotive use cases into a coherent data architecture linking urgency levels, functional units, and priority logic. However, a hard-wired algorithm alone is insufficient; unless these underlying mechanisms manifest as perceptible behaviors in the vehicle environment, the design remains incomplete. Therefore, these invisible structures must be embodied through the auditory and visual icons developed in the UX design process.

Priority Interaction Diagram

Urgency Level (Lexicographic Primary)
↓
WarningHigh (1) > WarningMiddle (2) > WarningLow (3) > Caution (4) > Feedback (5) > Notification (6)

Within Each Urgency Tier:
Unit Priority (Secondary Sort)
↓
Awareness > PrimaryControl > BrakeSystems > HighEmergency > LowEmergency > RoadSign > LowSafety > Media

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Within Each Unit:
Intra-Unit Rank (Tertiary Sort)
↓
Determined via cross-functional workshops

Figure 1: Hierarchical priority interaction: urgency dominates lexicographically, followed by unit priority, then intra-unit rank.

Table 3: Urgency and Unit Hierarchies with Visual Color Coding

Urgency Level Hierarchy

Priority	**Urgency Level**	**Color**
1	WarningHigh	Red
2	WarningMiddle	Orange
3	WarningLow	Amber
4	Caution	Cyan
5	Notification	Gray
6	Feedback	Green

Functional Unit Hierarchy

Priority	**Functional Unit**
1	ADAS Awareness
2	ADAS PrimaryControl
3	BrakeSystems
4	HighEmergency
5	LowEmergency
6	Road & Traffic Sign Cases
7	LowSafety
8	Media

Table 4: Hypothetical Sample of 24 Use Cases Demonstrating Urgency and Unit Classification (Set 1)

ID	**Feature**	**C.Priority**	**U.Level**	**Urgency**	**Unit**
1	A	1	1	WarningHigh	Unit A
2	B	1	1	WarningHigh	Unit A
3	C	2	1	WarningHigh	Unit B
4	D	2	1	WarningHigh	Unit B
5	E	3	2	WarningMiddle	Unit A
6	F	3	2	WarningMiddle	Unit A
7	G	4	2	WarningMiddle	Unit B
8	H	4	2	WarningMiddle	Unit B
9	I	5	3	WarningLow	Unit A
10	J	5	3	WarningLow	Unit A
11	K	6	3	WarningLow	Unit B
12	L	6	3	WarningLow	Unit B
13	M	7	4	Caution	Unit A
14	N	7	4	Caution	Unit A
15	O	8	4	Caution	Unit B
16	P	8	4	Caution	Unit B
17	Q	9	5	Feedback	Unit A
18	R	9	5	Feedback	Unit A
19	S	10	5	Feedback	Unit B
20	T	10	5	Feedback	Unit B
21	U	11	6	Notification	Unit A
22	V	11	6	Notification	Unit A
23	W	12	6	Notification	Unit B
24	X	12	6	Notification	Unit B

Table 5: Hypothetical Sample of 24 Use Cases Demonstrating Urgency and Unit Classification (Set 2)

ID	**Feature**	**C.Priority**	**U.Level**	**Urgency**	**Unit**
1	A	1	1	WarningHigh	Unit A
2	B	2	1	WarningHigh	Unit A
3	C	3	1	WarningHigh	Unit B
4	D	4	1	WarningHigh	Unit B
5	E	5	2	WarningMiddle	Unit A
6	F	6	2	WarningMiddle	Unit A
7	G	7	2	WarningMiddle	Unit B
8	H	8	2	WarningMiddle	Unit B
9	I	9	3	WarningLow	Unit A
10	J	10	3	WarningLow	Unit A
11	K	11	3	WarningLow	Unit B
12	L	12	3	WarningLow	Unit B
13	M	13	4	Caution	Unit A
14	N	14	4	Caution	Unit A
15	O	15	4	Caution	Unit B
16	P	16	4	Caution	Unit B
17	Q	17	5	Feedback	Unit A
18	R	18	5	Feedback	Unit A
19	S	19	5	Feedback	Unit B
20	T	20	5	Feedback	Unit B
21	U	21	6	Notification	Unit A
22	V	22	6	Notification	Unit A
23	W	23	6	Notification	Unit B
24	X	24	6	Notification	Unit B

4 UX Design

Following the computational model's systematic analysis, the UX design phase translates these analytical insights into concrete sensory experiences. In the visual domain, the primary goal is to communicate urgency through a clear color-coded system. Auditory icons, by contrast, operate on two complementary layers: metrical acceleration conveys the level of urgency, while timbre provides drivers with intuitive awareness of the functional unit of the vehicle associated with the warning. This dual structure ensures that auditory messages remain both perceptually grounded and semantically meaningful.

4.1 Visual Communication of Urgency

The dashboard implementation adopts a six-level chromatic hierarchy directly aligned with the urgency classification taxonomy, drawing on well-established principles from human-factors research and long-standing automotive display conventions. In this structure, warmer colors denote more critical conditions, while cooler tones represent lower-priority information.

WarningHigh appears in red (`#dc3545`), universally associated with danger and immediate action. WarningMiddle uses orange (`#fd7e14`), maintaining strong salience but reducing intensity. WarningLow transitions to amber yellow (`#ffc107`), consistent with traditional vehicle telltales signaling cautionary but non-critical conditions. Caution adopts cyan (`#0dcaf0`), helping drivers perceptually shift from warning to advisory states. Notification uses neutral gray (`#6c757d`), while Feedback employs green (`#198754`) to reinforce successful interactions. Together, these mappings support rapid recognition, reduce cognitive load, and ensure consistent interpretation across all 122 scenarios.

4.2 Auditory Design

The auditory design framework integrates multiple perceptual cues—including tempo, timbre, and spectral structure—to convey system intent and urgency with minimal cognitive

Table 6: Color-Coded Visual Urgency Communication System

Level	Urgency	Color	Hex Code	Perceptual Rationale
1	WarningHigh	Red	`#dc3545`	Maximum salience; immediate danger signal; strong attentional capture
2	WarningMiddle	Orange	`#fd7e14`	High salience; urgent but allows brief assessment time
3	WarningLow	Amber	`#ffc107`	Advisory warning; automotive standard for caution conditions
4	Caution	Cyan	`#0dcaf0`	Transitional advisory; maintains visibility with reduced urgency
5	Notification	Gray	`#6c757d`	Low salience; informational status updates
6	Feedback	Green	`#198754`	Positive confirmation; successful operation indicator

load. By coordinating these parameters across functional units and warning levels, the system establishes a coherent sonic language that supports rapid, pre-attentive driver interpretation.

4.2.1 Metrical Acceleration as Urgency Marker

In terms of auditory design, metrical acceleration conveys urgency through loop rate variations in warning sound files. The audio manager employs gapless looping for WarningHigh, WarningMiddle, WarningLow, and Caution categories through WebAudio API, ensuring uninterrupted auditory presence for persistent threats. Notification and Feedback categories trigger once without looping.

WarningHigh alerts employ the shortest loop interval (500 ms), creating maximum temporal density for immediate alerting. WarningMiddle doubles to 1000 ms, maintaining urgency while allowing processing time. WarningLow extends to 2000 ms, and Caution reaches 3000 ms for advisory conditions. Notification and Feedback do not loop (single-play). Loop rates specify inter-onset intervals; actual perceived tempo depends on sound-file duration. This systematic loop rate variation enables pre-attentive urgency discrimination—drivers perceive threat severity from repetition tempo alone.

Table 7: Loop Rate Specifications for Urgency-Level Audio Files

Level	**Urgency**	**Loop Interval (ms)**	**Loop Behavior**	**Perceptual Tempo**
1	WarningHigh	500	Continuous Loop	Very High
2	WarningMiddle	1000	Continuous Loop	High
3	WarningLow	2000	Continuous Loop	Moderate
4	Caution	3000	Continuous Loop	Low
5	Feedback	N/A	Play Once	Discrete
6	Notification	N/A	Play Once	Discrete

4.2.2 Timbre as Functional Unit Identifier

Timbre plays a crucial role in giving drivers intuitive awareness of the functional unit behind each warning, so I developed distinct sonic signatures by adjusting spectral content, attack characteristics, and harmonic structure. For Awareness-oriented cues, I selected bright, percussive mallet tones (spectral centroid 3.5 kHz, attack <10 ms) with rapid transients that cut through ambient noise and signal the need for cognitive focus. PrimaryControl feedback uses warm electric-keyboard timbres (spectral centroid 1.2 kHz, sustained harmonic series) that convey familiarity and calm. BrakeSystems employ flowing, modulated synthesizer textures with rhythmic movement (spectral flux variation >0.3), creating a subtle sense of momentum that mirrors intervention dynamics. HighEmergency cues build on resonant instrument tones with dense harmonic spectra (harmonic-to-noise ratio >15 dB) to command immediate attention, while LowEmergency and Media-related messages use clean, neutral electronic timbres (spectral centroid 2 kHz, minimal inharmonicity) appropriate for straightforward informational delivery.

Spatial audio positioning (specified in the Channels field) further reinforces functional categorization. Critical warnings (HighEmergency, BrakeSystems) use center-panned presentation for maximum attention, while directional threats (blind-spot warnings, cross-traffic alerts) employ left/right/rear spatialization matching hazard location. This multimodal coupling—timbre identifying the system, spatial position indicating threat direction—reduces ambiguity and ensures that the character of each warning naturally aligns with its intent, strengthening situational awareness and supporting safer driver responses.

5 Conclusion

This work presents a comprehensive, human-centered framework for designing and prioritizing in-vehicle warning sounds in the context of increasingly automated, electrified, and sensor-rich mobility systems. As traditional engine-noise cues diminish, safety-critical communication must rely on intentionally crafted auditory and visual alerts that reduce cognitive load while supporting rapid, intuitive driver responses.

The research introduces a multi-layered computational model that organizes 122 use cases into a coherent auditory-warning ecosystem. Through structured feature taxonomy, a refined six-level urgency hierarchy, functional-unit categorization, and a lexicographic priority-ordering algorithm, the model establishes a scalable method for resolving simultaneous alerts and ensuring perceptual clarity. The accompanying dashboard implementation demonstrates how these computational structures manifest as concrete UX artifacts, including color-coded visual indicators, metrical-acceleration–based urgency cues, timbre-based functional identities, and spatial audio positioning aligned with hazard direction.

The findings underscore that multimodal consistency—across sound, color, text, and spatialization—is essential for maintaining driver situational awareness. By providing a unified data architecture, the model enables ADAS teams, UX researchers, and designers to address a longstanding gap in OEM workflows: ensuring global coherence across warning systems without requiring a single dedicated oversight role.

5.1 Limitations and Future Work

The current framework is demonstrated through simulation; empirical validation through driving simulator studies and on-road testing remains essential to assess driver reaction times, perceptual confusion rates, and subjective acceptability across diverse user populations. Future work should include perceptual testing of timbre discriminability, validation of loop-rate urgency mappings under realistic noise conditions, and extension to fully autonomous vehicle scenarios where driver roles fundamentally shift. Additionally, cross-cultural studies examining color and sound associations in different markets would strengthen generalizability.

Ultimately, this framework advances both theoretical understanding and practical implementation of auditory displays, offering a robust foundation for future vehicle platforms that must balance automation with human trust, safety, and interpretability.

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