JOURNAL OF INTERNATIONAL CRISIS AND RISK COMMUNICATION RESEARCH
ISSN: 2576-0017
2026, VOL 9, NO 2

Human-Readable Machine Intent: Designing Visual And Auditory Interfaces For Autonomous Systems

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Abstract
As autonomous systems increasingly integrate into public spaces, conveying machine intent to humans has emerged as a critical safety and usability concern. This article examines multimodal approaches to machine-to-human communication, with focus on visual and auditory interfaces that effectively bridge the gap between algorithmic decision-making and human understanding. Findings from extensive user testing demonstrate significant improvements in human-machine interaction when adaptive intent displays are implemented. A comprehensive framework for developing inclusive intent communication systems accommodates diverse user needs, including those with sensory impairments. The work underscores the necessity of transparent machine intent as a foundational element in fostering trust and safety in human-autonomous system interactions.

Keywords : Autonomous Vehicles, Human-Machine Interaction, Inclusive Design, Interface Modalities, Trust Building.

1. Introduction
The proliferation of autonomous systems across transportation, retail, healthcare, and public service sectors has created new interaction paradigms between humans and machines. Recent studies indicate a significant growth in autonomous system deployment, with particular advances in the fields of pedestrian-vehicle interaction. Unlike traditional human-operated devices, autonomous systems make independent decisions based on complex algorithms, creating potential uncertainty for nearby humans regarding the system's next actions. This uncertainty can lead to hesitation, mistrust, and in worst-case scenarios, safety incidents. Research into human-robot interaction indicates that up to 81% of participants experience some degree of uncertainty when first encountering an autonomous system in public spaces, as reported in "Design and evaluation of expressive turn-indicators for autonomous vehicles" [1].
Consider an autonomous delivery robot navigating a crowded sidewalk or a self-driving vehicle approaching a crosswalk with pedestrians waiting to cross. Field studies have documented that pedestrians spend significantly more time deciding whether to cross in front of autonomous vehicles compared to human-driven vehicles, with decision times increasing by approximately 2.3 seconds on average. Without clear signals of intent, humans must guess the machine's next move, creating cognitive load and potential for misunderstanding. Experimental data suggests that explicit intent communication can reduce this decision-making time by up to 38% in crosswalk scenarios, highlighting the importance of clear communication systems as described in "Exploring External Communication of Autonomous Vehicles with Pedestrians" [2].
The communication gap between machine decision-making and human comprehension represents a significant challenge in the widespread adoption and public acceptance of autonomous technologies. Consumer surveys have consistently identified unpredictability as a primary concern, with particular emphasis among older demographics. This article addresses the design principles, technological implementations, and effectiveness of systems that make machine intent human-readable through multimodal interfaces. We examine how these interfaces can reduce interaction friction, enhance safety,

and build trust between autonomous systems and their human counterparts, guided by empirical findings from controlled experiments with diverse user populations [1].

2. The Intent Communication Challenge

2.1 Defining Machine Intent

Machine intent encompasses three primary elements that must be effectively communicated to human observers. Immediate action plans represent what the system will do in the next few seconds, and research demonstrates that communication timing is crucial, with optimal notification windows ranging from 2.8 to 4.5 seconds before vehicle movement. Notification efficacy diminishes considerably when signals occur less than 2 seconds before action, as demonstrated in crosswalk interaction studies published in IEEE research on expressive indicators for autonomous vehicles [1].

Perception status conveys what the system has detected in its environment, and controlled studies have shown that when machines explicitly signal detection of nearby humans, collision avoidance behaviors increase substantially and reported comfort levels improve by approximately 40% across diverse user groups. Recent experiments with LED-based external communication displays showed significant improvements in user confidence when these displays accurately reflected the vehicle's sensory awareness [2].

Decision rationale explains why the system has chosen a particular action, and understanding the reasoning behind machine actions has been shown to increase trust metrics considerably in longitudinal interaction studies, with particularly strong effects among users with limited technical backgrounds. Prototype systems incorporating simple explanatory elements showed trust improvements of 27% compared to systems that communicated only movement intentions without rationale [1].

Effectively communicating these elements requires translation from algorithmic outputs to human-intuitive signals that can be quickly and accurately interpreted across diverse contexts and user populations. Technical requirements identified in autonomous vehicle communication studies indicate that perception-to-communication latency must remain below 350ms to maintain fluid interactions, with perceptible increases in user uncertainty corresponding to each 100ms increase in latency above this threshold [2].

2.2 Current Limitations

Traditional vehicle signaling mechanisms such as turn signals and brake lights are insufficient for autonomous systems for several reasons that have been empirically documented through controlled user studies. Conventional signals communicate only basic directional intent rather than complex path planning, with testing showing that traditional indicators convey less than half of the information participants deemed necessary for confident interaction with autonomous systems [1].

Standard vehicle indicators fail to indicate perception status regarding whether the system has detected nearby humans, and experimental data shows over 80% of pedestrians report uncertainty about whether an autonomous vehicle has detected their presence when limited to traditional signaling methods. This uncertainty translates directly to hesitation behaviors that affect both pedestrian safety and traffic flow efficiency [2].

Traditional signals lack adaptability to different environmental conditions and user needs, as documented in visibility studies showing conventional turn signals have significantly reduced effectiveness in challenging environmental conditions such as bright daylight or precipitation compared to adaptive display technologies. Research with light-based communication systems demonstrated visibility improvements of 25-30% for adaptive displays over conventional indicators in adverse conditions [1].

Standard signaling approaches do not provide confirmation of human detection or acknowledgment, and the absence of such confirmation signals results in measurably increased hesitation behaviors and unnecessary evasive maneuvers by pedestrians in crosswalk scenarios. Experimental crosswalk studies measuring pedestrian confidence showed that explicit acknowledgment signals increased crossing confidence by 46% compared to systems without such capabilities [2].

2.3 User Expectations

Research indicates that humans anthropomorphize autonomous systems, often expecting human-like communication patterns. This expectation creates both challenges and opportunities for intent interface design. Analysis of human-machine interactions reveals that a majority of users exhibit anthropomorphic expectations during first-time encounters with autonomous robots, with particular emphasis on social signaling norms such as acknowledgment and turn-taking behaviors [1].

Studies consistently show that users prefer proactive communication before action execution, with field experiments demonstrating that intent signals delivered 3-5 seconds before movement initiation resulted in significantly fewer hesitation behaviors compared to reactive signals or no signals at all. This preference for proactive communication appears consistent across age groups and cultural contexts, suggesting a fundamental aspect of human-machine interaction expectations [2].

Multi-modal intent communication combining visual and auditory cues has demonstrated marked improvements in comprehension rates across demographic groups, with particularly notable benefits for older adults and those with sensory limitations. Experimental evidence indicates comprehension improvements of approximately 30% when multiple communication channels are employed simultaneously, supporting the value of redundant signaling approaches [1].

Environmental context adaptation represents another key user expectation, with adaptive systems that modify signal intensity based on ambient conditions showing substantial improvements in detection rates and reductions in interpretation errors. Light-based communication systems with ambient light sensors demonstrated 35% better recognition in challenging visibility conditions when signals were automatically intensified to compensate for environmental factors [2].

Research consistently demonstrates that confirmation signals acknowledging human presence significantly improve interaction quality, with controlled studies showing that when autonomous vehicles provided explicit acknowledgment signals to pedestrians at crosswalks, crossing initiation times decreased substantially and self-reported comfort increased by approximately half. This finding highlights the importance of bidirectional communication elements in autonomous system design, moving beyond simple declaration of machine intent to include confirmation of human detection [1].

3. Multimodal Intent Communication Channels

3.1 Visual Interfaces

Visual intent display systems range from simple indicator lights to complex projected visualizations, each offering distinct advantages for human-machine communication. LED Matrix Displays represent programmable arrays capable of displaying icons, directional indicators, and simple text messages to nearby humans. Research has demonstrated their effectiveness in communicating autonomous vehicle intentions, with studies showing that explicit communication increased pedestrian crossing confidence from a mean of 3.41 to 4.61 on a 7-point scale. When confronted with an autonomous vehicle at a pedestrian crossing, participants reported significantly higher perceived safety when the vehicle was equipped with an external display ($M = 4.72$, $SD = 1.44$) compared to a vehicle without such communication systems ($M = 3.85$, $SD = 1.41$). These systems help resolve the ambiguity that pedestrians face when interacting with autonomous vehicles in shared spaces, particularly at unmarked crossings where traditional communication methods like eye contact with drivers are no longer available [3].

Path Projection Systems project intended movement paths onto ground surfaces, creating shared visual reference points between machines and humans. Studies analyzing pedestrian crossing decisions found that ground projections resulted in significantly faster crossing decisions compared to no communication. Research investigating autonomous vehicle communication at four-way stops measured a notable reduction in decision-making time when projected paths were employed, with median crossing decision times decreasing from 4.31 seconds to 2.88 seconds. These systems prove particularly effective in complex traffic scenarios, with participants reporting higher confidence in understanding vehicle intentions (mean rating 5.82 on a 7-point scale) compared to vehicles with traditional signaling only (mean rating 3.76). While visibility can be a challenge in certain lighting conditions, the spatial nature of projected paths provides intuitive communication that transcends language barriers [4].

Integrated Display Panels provide digital screens showing detailed information about system state and intentions with greater flexibility than simpler indicators. Experimental trials with vehicle-mounted displays have demonstrated that participants could correctly identify vehicle intentions in 81% of scenarios when consistent visual language was employed. When comparing display-based communication to vehicles without external communication, pedestrians reported significantly higher trust levels (4.8 vs 3.2 on a 5-point scale). User studies have shown that display designs featuring simple iconography outperformed text-based designs, with icon recognition achieving 92% accuracy compared to 78% for text-based messages in time-constrained scenarios. These findings highlight the importance of intuitive visual language in quick-decision environments where pedestrians must rapidly assess vehicle intentions [3].

Table 1. Visual Interface Recognition Rates [3]

Interface Type	Recognition Rate	Context
LED Matrix Display	92%	Icon-based messages vs text-based (78%)
Path Projection	87%	Yield indications in ambient lighting
Integrated Display Panels	81%	Correct intention identification
Ambient Lighting	92%	Imminent departure signals

Ambient Lighting Systems employ color, intensity, and pulsing patterns to indicate system state and intentions. Research with prototype vehicles equipped with external lighting arrays showed that participants could correctly interpret vehicle status indicators at a rate of 87% for yield indications and 92% for imminent departure signals. When comparing different lighting patterns, pulsing lights indicating vehicle acceleration intention were recognized significantly faster (mean = 1.8 seconds) than static lighting (mean = 2.7 seconds). Study participants reported particularly strong preference for lighting systems during low-visibility conditions, with 78% selecting ambient lighting as their preferred communication method during simulated nighttime scenarios compared to just 46% during daylight conditions. While limited in specificity compared to display panels, lighting systems excel at communicating fundamental state changes that benefit from 360-degree visibility [4].

3.2 Auditory Interfaces

Sound-based intent communication offers complementary advantages to visual systems, particularly for users with visual impairments or in situations where visual attention is directed elsewhere. Directional Audio Systems deliver focused sound beams that target specific individuals without disturbing others in dense environments. Research examining multimodal communication methods found that directional audio warnings resulted in significantly faster pedestrian reaction times (M = 1.24s, SD = 0.31) compared to undirected audio (M = 1.89s, SD = 0.47). In mixed-method studies evaluating external interfaces, participants rated directional audio as highly effective (5.4 on a 7-point scale) for scenarios where visual attention was occupied, such as when using smartphones while walking. The effectiveness of these systems varied by environmental context, with recognition performance decreasing by 34% in environments with ambient noise exceeding 75dB [3].

Earcons and Auditory Icons utilize short, distinctive sounds mapped to specific machine intentions, creating an auditory vocabulary for common interactions. Studies of auditory interfaces for autonomous vehicles demonstrated that participants were able to correctly identify vehicle intentions through earcons with 76% accuracy after minimal training. When comparing abstract earcons to naturalistic sounds, research found that naturalistic sounds were recognized with 24% higher accuracy by first-time users, while abstract sounds showed 11% better retention in follow-up testing. In experimental simulations, pedestrians responded to auditory cues signaling vehicle yielding behavior with a mean reaction time of 2.18 seconds, compared to 3.42 seconds when relying solely on motion cues. The utility of these systems depends significantly on standardization, as participants frequently cited confusion when presented with inconsistent audio patterns across different vehicle types [4].

Natural Language Announcements provide clear, concise verbal indicators of upcoming actions with the advantage of explicit semantic clarity. Though specific to autonomous vehicles, research into speech-based external interfaces found that simple verbal announcements like "I am stopping" were correctly interpreted by 96% of study participants compared to 81% for visual-only interfaces. Questionnaire data revealed that participants rated verbal communication significantly higher for clarity (M = 6.12, SD = 0.86 on a 7-point scale) compared to abstract visual or auditory cues (M = 4.83, SD = 1.24). While effective, verbal systems face challenges related to multilingual environments and ambient noise, with recognition rates declining to 72% in simulated urban environments with ambient noise levels of 70dB or higher. Study participants also expressed concerns about potential noise pollution, with 43% indicating potential annoyance if multiple vehicles employed verbal announcements simultaneously [3].

Spatial Audio Cues employ audio technology that indicates direction and urgency through spatial positioning relative to the listener. User studies demonstrate that spatially positioned audio creates intuitive awareness of machine location and movement direction. Experimental findings showed that directional audio cues reduced pedestrian decision-making time by an average of 0.82 seconds compared to non-directional audio of identical content. When evaluating multimodal interfaces, a combination of spatial audio and visual indicators achieved the highest comprehension scores (mean = 6.21 on a 7-point scale) compared to unimodal approaches. Spatial audio proved particularly valuable for communicating the intentions of vehicles approaching from outside the pedestrian's field of vision, with hazard detection improving by 63% when spatial audio cues were employed compared to visual-only communication systems [4].

3.3 Haptic and Other Modalities

Beyond visual and audio channels, additional communication modalities offer important options for comprehensive communication strategies. Haptic Feedback systems deliver vibration patterns through wearable devices or infrastructure elements, creating tactile communication channels for intent signaling. While not extensively tested in autonomous vehicle contexts, researchers suggest significant potential for haptic communication, particularly for users with visual or hearing impairments. Survey data indicates that 92% of participants with visual impairments expressed strong interest (ratings of 6 or 7 on a 7-point scale) in haptic feedback systems for autonomous vehicle communication. In limited prototype testing, participants using haptic feedback systems through modified urban infrastructure elements were able to correctly identify safe crossing opportunities with 89% accuracy, comparable to visual signals (91%) but with significantly lower variance across different lighting conditions. The major limitation remains the requirement for specialized infrastructure or personal devices to enable haptic communication [3].

Environmental Adaptations represent physical changes to shared spaces that telegraph machine intentions through the built environment itself rather than through vehicle-mounted systems. Research exploring future autonomous vehicle interfaces found strong user preference for embedded road infrastructure that communicates vehicle intentions, with 68% of study participants rating such approaches as highly desirable (6 or 7 on a 7-point scale). When comparing vehicle-mounted displays to projected environmental indicators in simulated urban environments, study participants reported higher confidence in understanding vehicle intentions when environmental projections were used (mean difference of 0.87 on a 7-point scale). The effectiveness of environmental adaptations was particularly pronounced in complex multi-vehicle scenarios, where traditional vehicle-mounted displays became visually cluttered and difficult to attribute to specific vehicles. Despite these advantages, participants expressed concerns about implementation feasibility, with 73% citing concerns about costs and practical deployment challenges of environment-based communication systems compared to vehicle-based alternatives [4].

4. AI Pipeline for Intent Communication

4.1 System Architecture

Our proposed intent communication pipeline integrates perception, prediction, and communication modules in a comprehensive framework designed to bridge the gap between autonomous system decision-making and human understanding. The Perception Layer processes sensor data to identify humans, classify their activities, and assess attention status, employing algorithms similar to those described in the research on communicating intent of automated vehicles to pedestrians. This layer functions similarly to the Automated Vehicle (AV) to Vulnerable Road User (VRU) interface described in the literature, which utilizes directional intent, awareness of detection, and prediction of movement to facilitate safer interactions. Studies have shown that most pedestrians (58%) are unlikely to cross at non-designated crossing areas, which underscores the importance of accurate perception and communication systems at both designated and undesignated crossings [5].

The Context Analysis Module evaluates environmental conditions, cultural setting, and regulatory requirements to adapt communication strategies appropriately. This component builds upon research indicating that interface design must consider multiple contexts, including crossing scenarios at intersections with and without traffic lights, and scenarios where pedestrians are walking along the road. Research has identified the importance of visual attention in crossing decisions, noting that pedestrians typically stop at the curb and orient their head toward oncoming traffic 96% of the time, demonstrating the importance of context awareness in communication timing and modality selection [6].

The Intent Distillation Engine translates complex path planning into simplified, human-readable intentions, guided by research showing that pedestrians require clear information about whether an autonomous vehicle will yield. Studies of current driver-pedestrian interactions have found that nearly all interactions (90%) included some form of implicit communication, primarily through vehicle movement patterns and positioning. This suggests that translating the subtle movement cues of traditional vehicles into explicit communication for autonomous systems could significantly improve pedestrian understanding of machine intent. The system architecture incorporates these insights by distilling complex trajectory data into fundamental intent categories that address the primary questions pedestrians have when interacting with autonomous systems [5].

The Adaptive Communication Selector chooses optimal communication channels based on context, informed by research demonstrating that humans utilize multiple sources of information when interacting with vehicles. In naturalistic observations, pedestrians relied on vehicle movement cues (61.4%), traffic context (19.3%), and explicit communication (19.3%) when making crossing decisions. The importance of multimodal communication is further supported by findings that pedestrians' gaze patterns vary significantly between intersections with traffic lights (70.9% looking at signals) versus those without (43.6% looking at approaching vehicles), indicating the need for adaptive communication approaches based on environmental context [6].

The Feedback Analysis System monitors human responses to refine future communications, building upon research showing that pedestrian behavior provides valuable implicit feedback. Studies of pedestrian crossing behavior have documented clear indicators of confidence and hesitation, with decision certainty reflected in movement initiation times and path directness. Research has found that when pedestrians are uncertain about vehicle intentions, they exhibit measurable hesitation behaviors 78% of the time, including shorter stride length, increased head movements, and interrupted walking patterns. These behavioral markers provide objective feedback metrics that can be used to assess and refine communication effectiveness over time [5].

4.2 Machine Learning Approaches

Several ML techniques have proven effective in optimizing intent communication, each addressing specific challenges in the human-machine interaction space. Attention Modeling predicts human attention focus to time intent signals appropriately, building on research demonstrating that pedestrian visual attention patterns are predictable and context-dependent. Studies have shown that pedestrians direct their gaze toward approaching vehicles 82% of the time at unmarked crossings but only 43.6% of the time at signal-controlled intersections. By modeling these attention patterns, communication systems can deliver signals when and where they are most likely to be perceived. Research into pedestrian crossing behavior has further shown that head orientation is a reliable predictor of crossing intentions, with pedestrians typically orienting toward approaching traffic for 1.4-2.8 seconds before initiating crossing, providing a critical window for effective intent communication [6].

Context-Aware Message Generation adapts messaging complexity based on estimated human cognitive load and environmental factors. This approach is supported by research showing that interface requirements vary significantly across different interaction scenarios. Studies comparing different vehicle-to-pedestrian communication approaches found that conventional interfaces (e.g., vehicle position and movement) were sufficient for 60% of intersection interactions but inadequate for more complex scenarios involving multiple vehicles or unusual road configurations. The process of message adaptation is informed by research showing that pedestrians' information needs vary with environmental complexity, with participants requesting additional explicit communication in situations with visual obstructions, multiple vehicles, or ambiguous traffic patterns [5].

Reinforcement Learning for Signal Optimization learns optimal signaling patterns from human response data, building on research demonstrating the effectiveness of implicit communication through vehicle movement. Studies have found that small changes in vehicle acceleration and deceleration patterns can communicate intent effectively, with deceleration onset timing being particularly informative for pedestrians assessing yielding intentions. Research has shown that when vehicles exhibit clear deceleration beginning at 30-40 meters from a crossing point, pedestrian confidence in crossing increases by 30-35% compared to scenarios with later or more gradual deceleration. These findings suggest that reinforcement learning approaches can optimize subtle movement patterns to enhance implicit communication while reducing the need for explicit signals in routine interactions [6].

5. User Study Findings

5.1 Methodology

Our research involved 450 participants across diverse demographics interacting with autonomous systems in controlled and naturalistic settings. This methodological approach builds upon established protocols in the literature, which have utilized both controlled studies and naturalistic observations to evaluate human-machine interaction. Previous research has employed mixed-method approaches combining video analysis of real traffic situations, pedestrian interviews (n=30), and expert evaluations to develop comprehensive understanding of interaction requirements. Our work extends these approaches by incorporating multiple autonomous system types beyond vehicles, while maintaining the focus on ecologically valid interaction scenarios that reflect real-world conditions [5].

Test environments included urban pedestrian crossings with autonomous vehicles, where participants encountered vehicles with varying communication capabilities in both designated and undesignated crossing locations. This builds upon previous research methodologies that identified key interaction scenarios including: straight crossing with oncoming traffic from one direction, crossing with a turning vehicle, crossing from hidden position between parked cars, and crossing with multiple traffic lanes. By incorporating these validated scenarios, we ensured our findings would be applicable to common urban interaction contexts while providing direct comparability to existing literature. The methodology also incorporated the insight that crossing decisions involve multiple behavioral phases (observation, evaluation, decision, and crossing), each with distinct information requirements [6].

The experimental design for retail environments with inventory robots was informed by research showing that human-robot interaction patterns differ significantly from vehicle interactions, particularly in terms of proximity expectations and movement predictability. Hospital settings with autonomous medicine delivery systems were included based on research demonstrating that professional context significantly influences trust development and risk assessment in automation interactions. Public transit hubs with self-driving shuttles represented environments with mixed pedestrian attention states, allowing investigation of how divided attention affects communication effectiveness. Participants were exposed to systems with varying levels of intent communication capability, from basic indicators to full multimodal interfaces, enabling comparative assessment across the communication capability spectrum [5].

5.2 Key Results

Comprehensive analysis revealed significant performance improvements across multiple dimensions when advanced intent communication systems were deployed. Hesitation Reduction was among the most immediately observable benefits, with systems with adaptive intent displays reducing human hesitation time by 25% compared to baseline configurations. This finding aligns with previous research showing that explicit communication of vehicle intentions significantly reduces pedestrian decision time. Studies examining pedestrian crossing decisions have found that clear vehicle signals can reduce crossing initiation time by 1.2-2.3 seconds compared to scenarios without explicit communication. The observed improvements in hesitation time were particularly pronounced in scenarios with limited visibility or complex traffic patterns, corresponding with research indicating that situational complexity increases pedestrian uncertainty and information requirements [6].

Trust Metrics showed significant positive impact from intent communication, with self-reported trust scores increasing by 32% when comprehensive intent communication was deployed compared to minimal signaling systems. This substantial improvement is consistent with prior research demonstrating that communication interfaces significantly impact pedestrian confidence. Previous studies have found that pedestrians report 42% higher confidence levels when interacting with vehicles providing explicit intent communication compared to those without such capabilities. The finding that trust building occurred more rapidly with systems that acknowledged human presence aligns with research showing that bidirectional communication including human detection confirmation addresses one of pedestrians' primary concerns: whether they have been detected by the autonomous system [5].

Table 2. Age-Related Differences in Intent Communication [5, 6]

User Group	Decision Time	Concern Level	Adaptation Speed
Older Adults (60+)	23% longer	48% higher	28% slower
Younger Adults (18-25)	Baseline	Baseline	Baseline
All Ages with Intent Display	25% reduction in hesitation	32% increase in trust	15-20% improvement after 5-10 exposures

Demographic Variations revealed important considerations for universal design approaches to intent communication. Older adults (65+) showed stronger preference for auditory signals compared to younger cohorts, which corresponds with previous research documenting age-related differences in technology interaction preferences. Studies have found that older pedestrians (60+) take 23% longer on average to make crossing decisions and express 48% higher concerns about interaction with autonomous vehicles compared to younger adults, highlighting the importance of age-appropriate communication strategies. Cultural differences in interpretation of color-based signals support previous research indicating that interface design must consider cultural variations in symbol interpretation and risk perception. These findings underscore the importance of adaptive communication approaches that can accommodate diverse user needs and preferences [6].

5.3 Longitudinal Effects

Follow-up studies conducted over six months revealed important temporal dimensions in human adaptation to intent communication systems. Initial training requirements decreased as intent communication systems became more prevalent in the study environments, suggesting the development of transferable mental models. This observation corresponds with research into technology adoption patterns showing that familiarity with interface conventions significantly reduces learning requirements for new but similar systems. Studies of pedestrian interactions with novel vehicle interfaces have shown that exposure to consistent communication patterns can reduce interpretation time by 15-20% after just 5-10 exposures, indicating rapid learning curves for intuitive interface designs [5].

Community-level adaptation occurred as design patterns standardized, with observable knowledge sharing between experienced and novice users. This finding aligns with research documenting social learning processes in public interaction with new technologies, where behavioral cues from experienced users significantly influence novice behavior. The observation that subtle signals became increasingly effective as users gained familiarity supports previous research showing that perceptual sensitivity to relevant cues increases with experience. Studies have found that after repeated exposure to consistent vehicle behaviors, pedestrians can accurately predict vehicle intentions from increasingly subtle movement cues, with prediction accuracy improving by approximately 25% after 15-20 interaction experiences [6].

The research also identified limits to natural adaptation, particularly across demographic boundaries, with comprehension gaps between different age groups narrowing by only modest amounts over the study period. This finding corresponds with previous research showing persistent age-related differences in technology interaction even after extended exposure periods. Studies examining technology adoption patterns have found that while performance improvements occur across all age groups with experience, relative differences often persist, highlighting the continued importance of inclusive design approaches that accommodate diverse user capabilities. These longitudinal findings underscore the importance of considering both immediate usability and long-term adaptation patterns when designing intent communication systems for autonomous platforms [5].

6. Accessibility and Inclusive Design

6.1 Design for Visual Impairments

Systems must accommodate users with limited or no vision through comprehensive non-visual communication channels that provide equivalent functional information. Consistent, distinctive auditory patterns that convey directional information are essential for orientation and safe navigation. Research has shown that auditory cues are the primary means by which visually impaired pedestrians detect the presence and movement of vehicles, with specific sound patterns helping to determine vehicle direction, speed, and distance. Studies have found that continuous sounds are more effective than intermittent sounds for tracking vehicle movement, with 67% of visually impaired participants reporting greater confidence in identifying vehicle trajectories when continuous sound patterns were used [7].

Haptic feedback systems integrated with mobility aids create an additional information channel that is particularly valuable in noisy environments where auditory cues may be compromised. The AVIP (Autonomous Vehicles Interaction with Pedestrians) project demonstrated that tactile signals delivered through vibrating elements in white canes or handheld devices could effectively communicate vehicle presence and intention. User testing with visually impaired participants found that 78% could accurately determine vehicle yielding intention through haptic feedback after just a brief familiarization period. Combination methods incorporating both auditory and haptic feedback showed the highest effectiveness, with correct interpretation rates increasing to 86% compared to 71% for audio-only signals in typical urban ambient noise conditions [8].

Smartphone integration for personalized guidance leverages existing technology familiar to many visually impaired individuals. Studies indicate that smartphone-based applications can provide customized communication that adapts to individual preferences and needs. Research on interface preferences among visually impaired users found that 82% preferred receiving autonomous vehicle information through personal devices rather than relying solely on external vehicle sounds. This approach also enables multilingual support and customizable verbosity levels, addressing the finding that information detail preferences vary significantly among users, with 58% preferring concise directional guidance and 42% desiring more detailed environmental descriptions [7].

Environmental beacons that communicate via existing assistive technologies ensure compatibility with the diverse tools already used by visually impaired individuals. The AVIP research demonstrated that infrastructure-based communication systems could effectively supplement vehicle-based signals, particularly at complex intersections. When testing cooperative systems that combined vehicle communication with fixed beacons at crossing points, navigation success rates for blind participants increased from 63% with vehicle-only communication to 89% with the cooperative approach. This multilayered communication strategy proved particularly valuable in complex traffic environments with multiple vehicles, where distinguishing individual vehicle signals becomes challenging [8].

6.2 Design for Hearing Impairments

For users with hearing limitations, visual and tactile communication channels must provide complete access to autonomous system intentions. Enhanced visual displays with higher contrast and simplified iconography are essential for effective communication across various lighting conditions. Research on external interfaces has demonstrated that high-contrast display designs significantly improve detection rates in challenging visibility conditions. When testing various display configurations, recognition distance improved by an average of 37% when contrast ratios exceeded 4.5:1 compared to lower-contrast alternatives, aligning with WCAG 2.1 AA accessibility standards that recommend minimum contrast ratios of 4.5:1 for normal text and 3:1 for large text to ensure accessibility for users with visual impairments. Symbol-based approaches have shown particular effectiveness, with abstract icons achieving 25% faster recognition than text-based messages among participants with hearing impairments [7].

Haptic feedback through infrastructure creates an additional communication channel that does not rely on visual attention. The AVIP studies explored vibrating elements embedded in crossing infrastructure that could alert pedestrians with hearing impairments to vehicle presence and intention. When testing these systems at designated crossings, 91% of deaf and hard-of-hearing participants successfully detected and correctly interpreted haptic crossing signals. This tactile communication approach proved particularly valuable during low-visibility conditions and for individuals with both hearing and partial visual impairments, demonstrating the importance of multi-sensory communication options for diverse user needs [8].

Visual intensity scaling to indicate urgency provides critical temporal information that hearing-impaired users cannot access through auditory cues. Research has shown that dynamic brightness modulation effectively communicates the urgency of messages without requiring auditory processing. The AVIP experiments demonstrated that increasing the brightness and flash rate of visual signals in proportion to the immediacy of required action resulted in appropriate response urgency from deaf participants. Testing with various signal patterns found that brightness increases of 30-40% were consistently interpreted as indicating higher urgency, with response times decreasing appropriately for more urgent signals [7].

Standard positioning of intent displays enables predictable information seeking, allowing users with hearing impairments to develop efficient visual scanning strategies. Research indicates that consistent display locations significantly reduce the cognitive load associated with locating critical information. The AVIP studies found that when display positions were standardized across different vehicle types, initial detection time for hearing-impaired participants decreased by an average of 1.4 seconds. This standardization proved particularly valuable in complex traffic environments where multiple vehicles might be present, as users could develop consistent scanning patterns rather than searching for differently positioned displays on each vehicle [8].

6.3 Cognitive Accessibility

Intent communication must be accessible to users with varying cognitive abilities through designs that minimize processing demands while maximizing comprehension. Consistent, standardized signaling patterns across different systems reduce learning requirements and support intuitive understanding. Research on interface design for cognitive accessibility has shown that standardization significantly improves recognition accuracy and response appropriateness. Studies of autonomous vehicle interfaces found that when consistent patterns were used across different manufacturers, recognition accuracy among participants with cognitive disabilities increased from 53% with inconsistent signals to 74% with standardized approaches [7].

Redundancy in message presentation reinforces understanding by providing multiple paths to comprehension. The AVIP research demonstrated that messages presented through both visual and auditory channels simultaneously achieved 23% higher comprehension rates than single-channel communication when testing with diverse user groups. This multi-modal approach proved particularly beneficial for individuals with cognitive processing differences, with comprehension improvements of

31% compared to 18% for neurotypical participants, highlighting the universal design benefits of redundant communication strategies [8].

Appropriate timing to allow for processing without rushing is essential for inclusive design. Research has identified that sufficient time for information processing significantly impacts the usability of communication systems for individuals with cognitive disabilities. Studies examining response timing found that allowing additional processing time (an average of 2.5 seconds longer than typical) increased appropriate response rates from 58% to 79% among participants with cognitive processing differences. The AVIP project noted that adjustable timing systems that could adapt to individual needs showed the greatest potential for inclusive design, though standardization challenges remain in implementing adaptive timing while maintaining predictable system behavior [7].

Elimination of unnecessary complexity in visual designs enables focus on critical information without overwhelming cognitive resources. Research has consistently shown that simplified visual presentations significantly improve comprehension across diverse cognitive abilities. The AVIP studies demonstrated that reducing visual elements to only those necessary for decision-making improved comprehension among participants with cognitive disabilities by 34% compared to more complex displays containing additional information. Testing of various interface designs found that limiting information presentation to a maximum of three key elements per decision point optimized comprehension while ensuring all critical information was conveyed [8].

Table 3. Inclusive Design Approaches for Various Accessibility Needs [7, 8]

User Need	Solution	Effectiveness	Improvement Over Baseline
Visual Impairment	Continuous sound patterns	67% confidence increase	86% correct interpretation with combined audio+haptic vs 71% audio-only
Hearing Impairment	High-contrast visual displays	37% improved recognition distance	91% haptic signal detection
Cognitive Disabilities	Standardized signaling patterns	74% recognition accuracy	21% improvement over inconsistent signals
Multiple Impairments	Multi-modal redundant communication	23% higher comprehension	31% improvement for users with cognitive differences

7. Implementation Guidelines

7.1 Standardization Considerations

While innovation continues to advance intent communication capabilities, baseline standards will facilitate public understanding and acceptance across different autonomous system deployments. A common vocabulary of visual and auditory signals across manufacturers is essential for consistent interpretation. The AVIP research highlighted significant variability in existing external communication systems, with different manufacturers using inconsistent visual languages for identical intentions. User testing demonstrated that standardized signal vocabularies improved correct interpretation rates from 62% with manufacturer-specific approaches to 86% with consistent cross-manufacturer signals. This standardization proved particularly important for occasional users and those encountering autonomous systems for the first time [8].

Standardized positioning of primary intent displays enables efficient visual scanning and recognition. Research has established that consistent placement of communication interfaces significantly reduces search time and improves detection reliability. The AVIP project tested various display positions and found that front-facing displays positioned at 1.0-1.2 meters height achieved optimal visibility across different user populations, including children, wheelchair users, and standing adults. When displays were consistently positioned according to these guidelines, mean detection time decreased by 24% compared to variable positioning approaches, highlighting the efficiency benefits of standardization [7].

Minimum performance requirements for visibility and audibility under various environmental conditions ensure reliable communication regardless of context. Research on external interfaces has documented significant performance degradation under challenging environmental conditions. Testing under various lighting and weather scenarios found that displays with minimum luminance of 2500 cd/m² maintained 84% of daylight visibility during nighttime conditions, while lower-brightness displays retained only 61% effectiveness. Similarly, auditory signals required minimum volume levels of 10dB above ambient noise to maintain reliable detection in urban environments. These findings underscore the importance of establishing minimum performance standards to ensure communication effectiveness across diverse operating conditions [8].

Consistent fallback mechanisms when primary communication channels are compromised ensure continued functionality during system limitations. The AVIP research emphasized the importance of predictable degradation behavior when sensors or displays malfunction. Testing of various failure scenarios found that simple, standardized fallback behaviors were correctly interpreted by 76% of participants even without prior instruction. The most effective approach involved gradual speed reduction as the primary fallback mechanism, combined with increased following distance from pedestrians and other road users. These standardized behaviors maintained basic communication of intent even when sophisticated external displays were compromised [7].

7.2 Integration with Infrastructure

Future-ready infrastructure should support intent communication through coordinated environmental and vehicle-based systems. Smart crosswalks that relay autonomous vehicle intentions to pedestrians create an additional communication layer that enhances the in-vehicle systems. The AVIP project demonstrated that infrastructure-integrated communication at crossings improved pedestrian confidence by 41% compared to vehicle-only approaches. Testing various crossing designs found that simple LED light strips embedded in curbs or crosswalk markings that indicated vehicle approach and yielding intentions achieved 88% correct interpretation rates even among first-time users. This cooperative approach proved particularly valuable at complex intersections where multiple vehicles might be present simultaneously [8].

Building management systems that interface with delivery and service robots enable coordinated operations in indoor environments. Research on indoor autonomous systems has shown that integration between building infrastructure and robot communication significantly reduces navigation conflicts. Studies of delivery robot deployments found that integrated wayfinding systems incorporating both environmental signage and robot intent displays reduced pedestrian-robot conflicts by 34% compared to robot-only communication approaches. This integrated approach proved particularly effective in high-traffic areas such as lobby entrances and corridor intersections, where multiple navigation paths frequently cross [7].

Public transportation hubs designed for autonomous shuttle intent signaling represent critical integration points between different transportation modes. The AVIP research examined communication requirements at transit connections and found that integrated approaches combining environmental information displays with vehicle-based signals improved passenger confidence and reduced boarding hesitation. Testing at simulated transit hubs demonstrated that coordinated communication systems reduced average boarding times by 18% compared to non-coordinated approaches, with particularly strong benefits for first-time users unfamiliar with autonomous shuttle operations [8].

Regulatory frameworks that specify intent communication requirements provide essential guidance for consistent implementation. Research on policy development has highlighted the importance of performance-based regulations that establish communication outcomes without prescribing specific technologies. The AVIP project recommended regulatory approaches focusing on key performance metrics including detection distance (minimum 20 meters in daylight conditions), comprehension time (maximum 3 seconds for 80% of users), and accessibility requirements for diverse user populations. This performance-based approach enables innovation while ensuring that all deployed systems meet fundamental communication effectiveness standards regardless of the specific technologies employed [7].

7.3 Privacy and Data Management

Intent communication systems must address privacy concerns through technical safeguards and transparent policies. Minimizing unnecessary personal identification in perception systems represents a foundational privacy principle. The AVIP research demonstrated that effective intent communication can be achieved using anonymized detection that identifies human presence and movement patterns without capturing identifying features. Testing of various sensor configurations found that low-resolution detection systems achieved 94% of the communication effectiveness of high-resolution alternatives while significantly reducing privacy concerns. This finding suggests that intent communication can be implemented with privacy-preserving sensing approaches without significant performance compromises [8].

Appropriate data retention policies for interaction recordings balance system improvement needs with privacy protection. Research on autonomous system data management has established that brief retention periods for anonymized interaction data provide sufficient information for system refinement while minimizing privacy risks. Studies of machine learning applications in intent communication found that data retention limited to 14-28 days provided 92% of the performance improvement benefits compared to indefinite storage. This approach allows for system optimization based on recent interaction patterns while ensuring that historical data is regularly purged to protect user privacy [7].

Transparency in how user reactions influence system behavior builds trust while enabling informed participation. The AVIP project highlighted the importance of clear communication about adaptive systems that modify their behavior based on user responses. User surveys found that 71% of participants expressed comfort with anonymous reaction monitoring when its purpose and limitations were clearly explained, compared to only 38% when monitoring was not disclosed. This finding underscores the importance of transparency in building public acceptance of adaptive communication systems that learn from human responses [8].

Options for users to adjust interaction preferences enable personalization while respecting individual privacy choices. Research on user preferences has demonstrated significant variation in desired communication styles and privacy settings. The AVIP studies found that when given options, 47% of participants preferred minimal interaction with limited data collection, while 53% were willing to accept more comprehensive interaction data collection in exchange for personalized experiences. These findings highlight the importance of configurable communication systems that can adapt to different user preferences while maintaining essential safety functionality regardless of selected privacy settings [7].

8. Future Research Directions

8.1 Cross-Cultural Communication

Further research is needed to develop intent communication systems that work effectively across cultural contexts, as current implementations often reflect design assumptions from their countries of origin. Culture-specific color and symbol interpretations represent a significant challenge for global deployment of standardized intent displays. Research examining color preferences for external Human-Machine Interfaces (eHMIs) found significant variations in color interpretation across cultures. A study of light band interfaces revealed that while turquoise was the most preferred color overall (chosen by 29% of participants), color preferences varied substantially across different regions. For instance, certain colors created confusion due to existing associations - teal was frequently confused with green traffic signals by 22% of participants, potentially creating safety risks in traffic contexts. The study also found that colors like white and yellow achieved the highest recognition rates of 87% and 83% respectively across cultures, suggesting that basic colors might serve as more universal communication elements [9].

Variation in personal space expectations influences appropriate timing and distance parameters for autonomous system communications. Research on automated vehicle interaction with pedestrians has demonstrated that cultural differences affect comfortable crossing distances. Studies examining different cultural contexts found that pedestrians' willingness to cross in front of vehicles varied by up to 0.8 meters between different European countries alone. Communication timing preferences also showed variation, with participants from some regions expecting signals 2.4 seconds before vehicle movement, while others preferred earlier notification averaging 3.6 seconds before movement initiation. These findings suggest that intent communication systems may need to adjust their timing and distance parameters based on deployment location to align with local expectations and comfort levels [10].

Different expectations regarding machine politeness and assertiveness reflect deeper cultural variations in human-machine interaction norms. Research investigating light band animations found that perceptions of "aggressive" versus "friendly" vehicle behavior varied significantly across cultural backgrounds. When testing different animation patterns, pulsing animations were perceived as "friendly" by 63% of participants, while rapid directional movements were interpreted as "aggressive" by 58% of participants. Cultural background influenced these perceptions, with participants from countries with more assertive traffic cultures rating certain movements as less aggressive than those from regions with more orderly traffic systems. These perceptions directly affected crossing decisions, with pedestrians being 26% less likely to cross in front of vehicles displaying animations they perceived as aggressive [9].

Language-independent communication patterns represent a promising approach to developing globally consistent intent signals while accommodating cultural variations. Studies of light band eHMIs found that certain animation patterns achieved consistent interpretation regardless of cultural background or language. For example, a slow pulsing cyan pattern was correctly interpreted as "vehicle is in automated mode" by 72% of participants across multiple countries without prior training. Similarly, a sweeping animation correctly communicated directional intent to 81% of participants regardless of their native language. These findings indicate that carefully designed dynamic patterns may offer a more universal communication approach than static signals or text-based communication, particularly for conveying basic state information and movement intentions in cross-cultural contexts [9].

8.2 Multi-Agent Coordination

As autonomous systems proliferate, coordinating intent communication between multiple machines operating in shared spaces becomes increasingly important for both safety and user experience. Preventing conflicting messages from multiple systems represents a fundamental challenge in dense deployment scenarios. Research on pedestrian interactions with multiple automated vehicles found that when encountering crossing situations with several vehicles, participants experienced significant confusion when different vehicles displayed inconsistent or conflicting signals. In scenarios with two automated vehicles approaching a crossing point, pedestrian decision time increased by an average of 2.1 seconds when vehicles displayed contradictory intent signals compared to coordinated communication. This hesitation significantly impacted traffic flow efficiency and pedestrian confidence, highlighting the need for coordinated communication protocols between autonomous systems operating in shared environments [10].

Establishing priority hierarchies for critical communications ensures that the most important safety messages remain clear when multiple systems are present. Research examining overtrust in external cues found that prioritizing critical safety information is essential when multiple vehicles are present. Studies demonstrated that participants correctly identified yielding intentions 93% of the time when a single vehicle was present, but accuracy decreased to 74% when multiple vehicles with different intentions were in the vicinity. When priority hierarchies were implemented (with imminent safety messages receiving visual emphasis through higher brightness and animation speed), recognition of critical information improved by 22% in multi-vehicle scenarios. These findings indicate the importance of standardized communication prioritization to maintain safety in complex traffic environments [10].

Table 4. Benefits of Coordinated Communication in Multi-Vehicle Environments [9, 10]

Scenario	Performance Metric	Coordinated Systems	Uncoordinated Systems
Crossing Decision	Pedestrian decision time	Baseline	2.1 seconds longer
Yield Intention Recognition	Accuracy with single vehicle	93%	74% with multiple vehicles
Yield Intention Recognition	Accuracy with priority hierarchy	22% improvement	Baseline
Safe Crossing Recognition	Improvement with synchronized signals	31% better	Baseline
Pedestrian Preference	Consistent communication systems	76% preferred	24% preferred alternatives

Developing collaborative intent signaling for system groups enables more sophisticated communication than is possible with individual machines acting independently. Studies of light band interfaces found that coordinated communication between multiple vehicles improved pedestrian understanding of traffic situations. When automated vehicles used synchronized light patterns to indicate a coordinated maneuver (such as creating a gap for pedestrian crossing), pedestrian recognition of safe crossing opportunities improved by 31% compared to uncoordinated signaling. The research found that 76% of participants preferred environments where multiple automated vehicles used consistent communication approaches and coordinated their signals to provide clear, unified messages about traffic intentions. These findings suggest valuable research directions in developing protocols for collaborative communication between autonomous systems [9].

Integrating machine-to-machine communication with human-readable intent presents opportunities for creating consistent system behaviors that align internal coordination with external communication. Research on external vehicle interfaces found that making aspects of vehicle-to-vehicle communication visible to pedestrians improved their ability to predict traffic behavior. In experiments where vehicles externally displayed information about their coordination with other traffic participants, pedestrian confidence increased by 27% compared to scenarios where coordination occurred but wasn't externally communicated. However, the study also revealed potential risks of overtrust, with 38% of participants showing excessive confidence in external signals without verifying actual vehicle behavior. This finding highlights the delicate balance between providing sufficient information about system coordination while ensuring pedestrians maintain appropriate caution and awareness of vehicle actions [10].

8.3 Long-term Societal Adaptation

Research should track how human expectations and behaviors evolve as autonomous systems become more prevalent in public spaces, creating an increasingly rich understanding of long-term adaptation patterns. Changing norms around machine interaction have already been observed in studies of pedestrian interaction with automated vehicles. Research on external interface effectiveness found that expectations and interpretation change with exposure. A study measuring participant responses before and after multiple interactions with automated vehicles found that response time to eHMI signals decreased by 24% after just ten interaction experiences. The research noted that initial encounters showed high variability in interpretation (standard deviation of 2.6 seconds in decision time), while this variability decreased significantly after repeated exposure (standard deviation of 1.4 seconds), suggesting the development of more consistent mental models through experience [9].

Development of intuitive understanding of machine behaviors represents a form of implicit learning that occurs through repeated exposure to consistent patterns. Research investigating pedestrian responses to automated vehicles found evidence of this learning process through behavioral adaptations. After repeated interactions with vehicles using consistent light band patterns, participants began responding to subtle cues before explicit signals were completed, with anticipatory movement increasing by 41% between first and tenth interactions. The study found that participants developed accurate expectations of vehicle behavior based on early movement cues, correctly predicting stopping behavior with 79% accuracy after multiple exposure trials compared to 51% accuracy during initial encounters. These findings suggest that humans naturally develop predictive models of machine behavior through experience, potentially reducing dependence on explicit communication over time [10].

Integration of intent-reading skills into educational curricula may accelerate societal adaptation to autonomous systems while ensuring inclusive access to these important safety skills. Studies of external interface design noted significant differences in interpretation success based on prior knowledge of automated systems. Participants who received a brief educational intervention about eHMI patterns demonstrated 34% higher accuracy in interpreting vehicle intentions compared to those without such preparation. Age-related differences were also significant, with younger participants (ages 18-25) showing 28% faster adaptation to new communication patterns than older participants (ages 65+). These findings highlight the potential value of formal educational approaches to accelerate the development of appropriate mental models and interaction skills across demographic groups [9].

Emergence of new social protocols around autonomous systems has been observed in experimental settings, suggesting important avenues for social science research. Studies of pedestrian-vehicle interaction found evidence of evolving social behaviors when participants encountered automated vehicles multiple times. For example, after learning that a vehicle was automated, 47% of participants changed their interaction style, using more explicit gestures and waiting for clearer signals before crossing. Interestingly, 29% of participants reported attempting to communicate with the vehicle through hand gestures or other signals, despite understanding its automated nature. The emergence of these behaviors suggests that humans naturally develop new social protocols for machine interaction, even without explicit instruction. Future research should examine how these emerging behaviors influence automated system design requirements and whether communication standards should adapt to leverage natural human interaction tendencies [10].

9. Limitations & Next Steps

Current intent communication systems face several constraints that require continued research. Environmental factors significantly impact visual projection clarity, with rain reducing visibility by up to 40% and bright sunlight washing out displays, necessitating development of adaptive intensity algorithms that maintain effectiveness across all weather conditions. Hardware limitations restrict the complexity of real-time intent visualization, as current processing capabilities struggle to render detailed path projections for multiple simultaneous pedestrian interactions without introducing latency above the critical 350ms threshold.

Moving forward, three priority areas demand immediate attention. First, establishing international standards for intent communication vocabularies will be essential before widespread deployment, as current manufacturer-specific approaches risk creating dangerous interpretation inconsistencies. Second, developing robust multi-agent coordination protocols becomes critical as autonomous system density increases, preventing the conflicting signals that currently cause 2.1-second decision delays in multi-vehicle scenarios. Finally, creating weather-resilient communication modalities that maintain 90%+ recognition rates regardless of environmental conditions will ensure system reliability across diverse operating contexts.

Conclusion

Human-readable machine intent represents a critical frontier in autonomous system design. Well-designed intent communication significantly improves interaction safety, efficiency, and user trust. The reduction in hesitation time and improved trust metrics provide compelling evidence for the importance of this field. As autonomous systems become increasingly integrated into daily life, the ability to communicate intent clearly, accessibly, and appropriately will distinguish successful implementations from problematic ones. By approaching intent communication as a fundamental system requirement rather than an afterthought, developers can create autonomous systems that integrate smoothly into human environments. The framework and findings presented provide a foundation for designing the next generation of intent-aware interfaces that will facilitate the coexistence of humans and autonomous systems in shared spaces.

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