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Vehicle Automation–Other Road User Communication and Coordination: Theory and Mechanisms

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ABSTRACT When automobiles were first introduced in the early 1900s, poor communication and unsafe interactions between drivers and other road users generated resistance. This created a need for new infrastructure, vehicle design, and social norms to mitigate their negative effects on society. Vehicle automation may lead to similar challenges as drivers are supplanted by machines, potentially eliminating social behaviors that serve to smooth on-road communication and coordination. Through a review of communication, robotics, and traffic engineering literature, we explore the mechanisms that allow people to communicate on the road. We show the sensitivity of road users to signals that are sent through vehicle motion, suggesting a need to design vehicle automation kinematics for communication and not just external lighting signals. The framework further points to interdependence in communication where road users modulate their behaviors concurrently to exchange information and develop common ground. Designing automation to support common ground may smooth negotiations by generating interpretable signals in ambiguous situations. We propose a process to make automation observable and directable for other road users by considering vehicle motion during development of algorithms, interfaces, and interactions. Road users will be incidental users of vehicle automation—users whose goals are not directly supported by the technology—and poor communication with them may undermine the safety and acceptance of vehicle automation. As the reach of automation grows, communication among humans and machines may fundamentally change social interactions, requiring a framework to guide the process of making automation interactions smooth and natural.

INDEX TERMS Human factors, automation, autonomous vehicles, human–robot interaction, pedestrian.

I. INTRODUCTION

Vehicle automation may be the largest disruption to the transportation system since the original introduction of automobiles in the early 1900s [1]. Not only has vehicle automation been predicted to eliminate the approximately 94% of crashes that are attributable to human error [2], but it may also expand mobility to people who now have limited access. Much like this current disruption from automation, the introduction of human-driven automobiles in the early 1900s was not a seamless endeavor—new infrastructure and communication mechanisms were needed to resolve traffic conflicts between drivers and other road users. To illustrate how vehicle design, infrastructure, and social norms have affected traffic safety over the decades, from the 1930s, the motor vehicle fatality rate per 100 million miles traveled has decreased from 15.0 to 1.5 in the United States, still representing over 35,000 deaths per year. The promise of eliminating 94% of these crashes with vehicle automation would produce a fatal crash rate of 0.075 or 1,750 deaths; however, where automation eliminates certain error types, it often introduces new ones [3]–[5]. The introduction of vehicle automation is likely to present unforeseen challenges by uprooting decades of communication among people in favor of communication among both people and machines.

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Social interactions among road users are characterized by levels of uncertainty [6] and interdependence [7], which presents challenges of trajectory prediction for vehicle control [8]. In addition, control actions for vehicle automation-other road user interactions may not simply be related to safety outcomes, such as collisions, but also risk perception, politeness perception, and acceptance. For example, if a vehicle is unnecessarily aggressive while approaching a pedestrian, the vehicle could be perceived as impolite or risky. While dealing with complexity and uncertainty are necessary for getting from point A to point B, less obvious is how automation will manage interdependence with other road users in situations that require coordination, such as an intersection negotiation with a pedestrian.

Research on human-automation interaction often emphasizes its relationship to the "primary" user—the rider or driver of a vehicle with automation—whose goals are being supported by the automation [3], [9]. For primary users of vehicle automation, it can reduce their workload and give them the ability to perform tasks that they would otherwise be doing instead of driving. A neglected viewpoint is that of users whose goals are not being directly supported by and, in fact, may be in conflict with the automation—"incidental" users. We extend the definition of incidental users as passive users of technology who are not the intended user of it [9], [10]. Such incidental users will become common with the widespread adoption of robots and automation, increasing the need to consider them in the development of the technology. In the case of vehicle automation, these incidental users are the other road users, including vehicles, pedestrians, or cyclists. The best type of interaction for these users is one where the automation does not impede their ability to achieve their own goals. If their goals are impeded in an unacceptable way, negative beliefs among incidental users may undermine tolerance of vehicle automation and its predicted benefits [11].

Interactions with incidental users are also inherently coupled with the experience of primary users, both in terms of their moment-to-moment experience in the vehicle and the attitudes that they bring to using the automation. For example, creating automation that is too cautious may decrease the speed at which primary users arrive at their destinations. While vehicles will in most cases prioritize the experience of the rider, they will also need to consider how pedestrians perceive them. In traffic interactions, 74% of drivers stopped when they were legally required to do so, indicating preference of some drivers to prioritize their own goals over those of the pedestrians [7]. This may be related to the timing of the situation, creating conditions in which stopping is not appropriate, and also characteristics of the users, such as their attitudes toward wealth or their social class [12]. Therefore, resolving the challenge of interdependence for both primary and incidental users may be necessary for vehicle automation to be accepted. Such system-wide effects inform a network perspective of people who interact with automation [13].

This paper focuses on how vehicle automation will interact with its incidental users—other road users. Figure 1 shows an example intersection negotiation where a vehicle and pedestrian must communicate. These interactions are characterized by both the trajectories of the vehicle and pedestrian, as well as additional signals (e.g., hand wave) that each agent may introduce to smooth the interaction. For example, during a crosswalk negotiation vehicles and pedestrians may adjust their behavior to indicate their intent to cede the right-of-way [14]. This negotiation involves an interaction between the vehicle, pedestrian, and context, including conventions governing their behaviors. Our focus is on the psychological aspects of communication that support interactions between vehicles and incidental road users rather than a specific technology (e.g., Dedicated Short Range Communication). The contribution of the paper is fourfold: 1) describe how communication influences trust, acceptance, and tolerance of vehicle automation by incidental users, 2) clarify the problem of vehicle-other road user communication to elucidate gaps in the literature, 3) situate vehicle-other road user interaction theory within the communication and joint action literatures, and 4) provide a framework to inform research and design of communication between incidental users and vehicle automation.

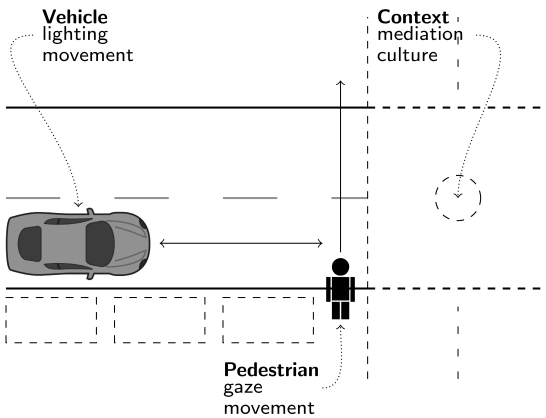

FIGURE 1. Example crosswalk negotiation between a vehicle and pedestrian in a road context.

II. TRUST, RISK, TOLERANCE, AND ACCEPTANCE

Many studies have explored the need for vehicle automation to communicate with other road users [15]–[17]; however, rarely do these studies operationalize the negative consequences that they are trying to prevent (e.g., low acceptance). To address this limitation, we examine constructs associated with the consequences of automation design, such as trust and perceived risk [18], [19]. In addition, we discuss the benefits and limitations of two technology acceptance frameworks that have implications for the perceptions of incidental users [20], [21]. The resulting synthesis provides direction on how we might evaluate competing communication strategies.

Trust and acceptance are related topics that have been investigated in the context of vehicle automation [18], [22].

Incidental users whose trust is miscalibrated to vehicle automation may interact with it in unsafe or inefficient ways, such as stepping into the roadway before the vehicle clearly indicates that it is going to stop. Recent surveys have shown relatively low trust among the public for vehicle automation [22]–[24]. Typical responses from survey participants include that they do not trust vehicle automation because of concerns about its capability, as well as the desire for a sense of control [22] and system transparency [25]. Communication from vehicle automation may reduce the effects of low initial trust by making the vehicle's intent or state interpretable or by invoking mechanisms to repair trust when it is violated [26]. Such systems may sacrifice efficiency for politeness, improving pedestrian perceptions and tolerance of the automation regardless of whether it impedes their distal goals.

A parallel concern for the vehicle automation is risk perception [11], [19]. Automation failures (i.e., automation surprises) can lead to a unique form of risk known as dread risk which is associated with uncontrollable and mysterious causes. Terrorism or nuclear power lead to this kind of perceived risk [27]. Overestimating risk may arise from the inability to think of uncertainty probabilistically, the memorability of events, and perceptions of consequences [27]. In addition, people generally consider the trade-off between benefits and risks, which is particularly important for incidental users, whose goals may not be supported by the automation [28]. High profile crashes as well as low initial trust may result in interactions as incidental users having a larger effect on risk perception, making them critical for the acceptance of vehicle automation [22], [24], [25]. Communicating the vehicle's intent or state, particularly in response to the movement of the pedestrian, could provide understanding and a sense of control based on the vehicle's actions, mitigating these sources of dread risk.

Historically, the Technology Acceptance Model has been used as a foundation for connecting technology design, acceptance, risk perception and trust to predict the use of technology [20], [29], [30]. Indeed, some researchers have used it to predict use of vehicle automation [25], [31]. However, the Technology Acceptance Model does not consider different types of users, such as incidental users, whose experiences may contribute to beliefs about vehicle automation regardless if they accept and/or adopt the technology. The concern about incidental users' experiences is not primarily concerned with the automation helping to achieve their goals but what could be called tolerance—the absence of negative attitudes about the technology could undermine road users' willingness to cooperate. This suggests both a concern about how individual attitudes influence group attitudes as well as an intermediate stage before acceptance and/or adoption. A complementary approach is needed to describe these societal effects of their beliefs.

The Diffusion of Innovations Theory [21] focuses on group effects over time, where the likelihood of acceptance or adoption is based on the probability of someone in a population adopting it. Thus, features of a technology increase the likelihood that members of a group will adopt it. Adoption is influenced by the technology's relative advantage (e.g., cost and/or time saved), compatibility (e.g., relation to values and experiences), observability (e.g., visibility and ability to describe to others), complexity (e.g., usability and understanding), and trialability (e.g., ability to experience the system) [21]. The stage where these characteristics of the innovation are considered is known as the ''persuasion'' stage where someone is deciding whether to adopt the technology. The observability and trialability of a technology may reduce perceived risk because they enhance the sense of control or agency provided by the technology. This theory suggests that vehicle automation communication that improves an interaction, fits with the goals of incidental users, is easy to understand, and that can be tested, will be more successful than alternatives.

The combination of the Technology Acceptance Model and Diffusion of Innovations theory shows how individual effects on trust and perceived risk can be translated into larger societal effects. Indeed, concerns about perceptions of transparency, control, and technical competence may be amplified if incidental users' experiences are negative and result in poor tolerance of vehicle automation [22], [25]. One solution is developing clear vehicle automation-other road user communication and coordination that is least disruptive by taking advantage of existing mechanisms for smooth and natural communication, which can be informed by historical approaches to communication.

III. COMMUNICATING WITH PEOPLE

Communication research has a long history of progressing in tandem with the development of technology, ranging from signal processing theories to more recent explorations of social media networks. As a result, early questions provide a foundation for the development of new communication technologies, such as the universal questions of communication that are concerned with accuracy, meaning, and effect of communication [32]. Unfortunately, communication research has not been considered in formulating the concepts and categories used when describing vehicle automation communication strategies. The result informs a narrow view of communication that limits the breadth of engineering solutions that have been considered. As such, the communication literature can give a more structured account of the factors involved in vehicle-pedestrian interactions.

The earliest communication models involved a sender encoding a signal that is sent over a channel and then decoded and interpreted by the receiver. However, like most communication [33], vehicle automation communication involves interdependence and coordination. Coordination requires monitoring and adjusting to ensure the understanding of the other, and responding with additional messages and actions [34]. Our framework includes how meaning is developed and shared, what happens when a message is not sent or received accurately, and how communication fits into a taxonomy of codes, cues, and channels.

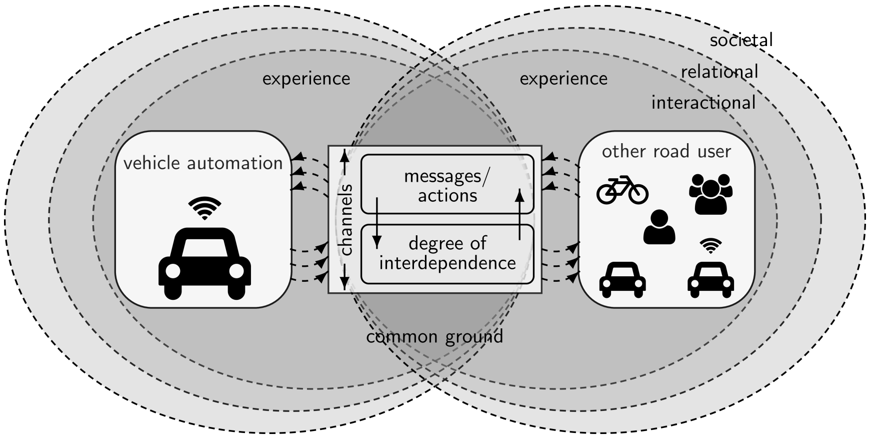

FIGURE 2. Transactional model of communication adapted for vehicle-other road user interaction.

Interdependence has been described through joint activity theory, which explains how people coordinate to reach a desired and mutual goal [33], [35]. The concept of common ground—shared knowledge, beliefs and assumptions between two people communicating—is a key component for coordinating interdependent agents [33]. For example, if a driver and pedestrian are negotiating an intersection, the presence of common ground helps understand who has right-of-way and the meaning of their movements and gestures. Specifically, the driver and pedestrian may understand a common set of rules or exchange information to develop mutual understanding and determine priority. The process of sustaining, updating, and repairing common ground is necessary to avoid catastrophic miscommunication, such as collisions [5], [34]. This process occurs within the context of an interaction and includes monitoring for understanding to update common ground and adjusting the communication strategy. Therefore, monitoring the vehicle is as important as monitoring the incidental user for understanding. Drivers and pedestrians may each interleave many behaviors before achieving sufficient common ground to negotiate an intersection. Common ground is a concept that helps us think about someone else's thinking to coordinate decisions. Technology that supports common ground will lead to better coordination by aligning vehicle automation and incidental user expectations.

Common ground can be thought of as occurring within overlapping "fields of experience" where the interaction among people dynamically increases or decreases the overlap [36]. Social, relational, interaction, and experiential contexts also contribute to the extent to which the "fields of experience" can overlap and how quickly they might overlap [37]. Fig. 2 incorporates these contexts and shows a conceptual model of vehicle automation-incidental user communication based on other historical models [32], [36], [37]. Considering "fields of experience" and context in an overall framework has advantages because, for example, cultures can vary considerably in how lights on the vehicle are used for communication [38]. Also, social context can dictate the rules and norms that define communication [39], such as what to do when two people stop simultaneously at a stop sign. A key aspect of this conceptual model is how the degree of interdependence determines the information exchange required to develop common ground, as shown by the amount of overlap in Fig. 2. The transactional model of communication captures this interdependence by focusing on the message itself rather than the sender or receiver alone [37], [39]. In traffic there is a continuous exchange of messages and feedback that influences future actions and is informed by cultural contexts, rules, and norms. Vehicle automation may need to represent these contexts in the design of communication signals. For example, a vehicle may communicate its assertiveness differently through its trajectory or lighting, depending on the context.

Communication models generally share the terminology of codes, channels, cues, and signals. Fig. 3 shows how these terms are related in a cycle of feedback and interaction. As an example, a vehicle en*code*s distance information over a visual *channel* that produces the *cue* of looming, which results in a *signal* of whether the vehicle is stopping for a pedestrian. Fig. 2 shows how this process takes advantage of common ground and scaffolds new common ground to negotiate the crosswalk.

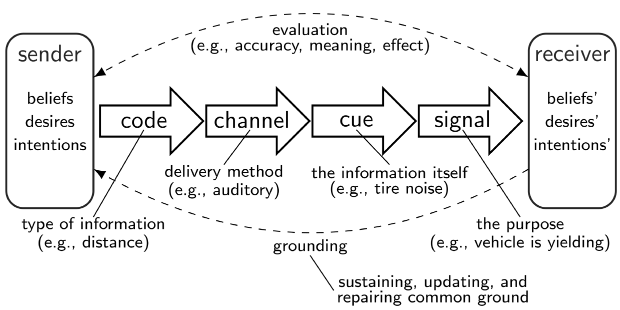

FIGURE 3. Relationship between communication terms.

Codes are the ''systematic means through which meanings are created, transmitted, perceived, and interpreted'', such as different nonverbal codes [40]. Codes can be thought of as the type of information being sent (e.g., distance information). Whereas the verbal communication code is associated with the meaning of words, nonverbal codes are typically classified into eight categories: kinesics, vocalics, physical appearance, proxemics, haptics, chronemics, environment and artifacts, and olfactics. Channels can be thought of as the modalities through which the codes are used [41]. This distinction is useful because proximity can be communicated visually (e.g., seeing a car approaching) and auditorily (e.g., hearing a car approaching). Cues are the action, word, or sound from the senders perspective—the action, word, or sound itself—whereas signals are the social meaning of the cue—the interpretation of the receiver [42]. Cues allow people to coordinate their actions by signaling to another person potential next actions; for example, the cue of handing someone an object is a signal for the other person to grasp it [43]. Social cues and signals are, therefore, ''emotionally, cognitively, socially, and culturally based,'' which can be seen with the contextual factors in Fig. 2 [42]. Fig. 3 shows elements of communication that can be used to create combinations of these social cues and signals that reinforce the communication between road users shown in Fig. 2.

Road users communicate through nonverbal cues, including through movement, vehicle lighting, and engine noise. Nonverbal communication is primary due to its early evolutionary basis that translates into cross cultural and even cross species understanding [40]. The majority of cues on the road, due to their dynamic nature, are through the codes of proxemics, kinesics, and chronemics, or the use of movement, space, and time for communication. Kinesics can include many aspects of movement including gait, head, and eye. Proxemics is the use of distance to communicate [44]; for example, a vehicle that moves into a crosswalk when there is a pedestrian waiting may be perceived as rude. Chronemics is how events are arranged in time for communication. For example, delaying a message can communicate the difficulty of a decision or uncertainty [45]. These codes may use visual or auditory channels to produce different cues. For example, road or car noise can indicate proximity and movement. Taken together, proxemics, kinesics, and chronemics codes can be used to understand the breadth of communication designs and to describe road user behavior.

The communication theory presented here can guide engineers to understand the mechanisms of communication, which can provide insight into the variables that are needed for designing communication strategies. Communication theory provides a way to design communication (i.e., codes, cues, and channels) and evaluate those designs (i.e., signals) within an overall framework. One way to think about how these inform the design of a vehicle automation communication strategy is to think of these ways of categorizing communication as variables that could be implemented in a design study. Additionally, the effect of those variables on outcomes such as trust or perceived risk could provide a connection between communication theory and the effects of automation. With these tools as our foundation, we can consider more complex topics, such as joint action theory.

IV. COMMUNICATING THROUGH ACTION

Using action for communication is not a new concept, with early examples showing how proxemics, kinesics, and chronemics and other nonverbal codes could be used in animation to tell a story [46]. For example, timing can be used to define weight and size through exaggeration (e.g., elongating a crouch when jumping to signify the strength of the jump). Lasseter [46] used movements like these to convey the relationships between characters in animated films. Communicating and coordinating among road users can be thought of similarly, with interactions defining the relationships. The relationships between vehicle automation and incidental users will be interdependent, suggesting that they will have to understand the social and cognitive aspects of the scenario to interleave their behaviors. As indicated in the previous section, one theory that has been used to explain interdependent action is joint activity theory, which describes how two or more people coordinate their actions [33], [47]. Joint activity theory extends communication theories to the design of interaction for communicative automation by describing how to design interdependent actions [48]. Vehicle automation that incorporates joint action theory may signal its intent more clearly by using specific maneuvers and have templates for series of actions depending on an interaction. Joint action theory informs a view of vehicle automation communication where movement is inherent in the communication strategy, and thus reconciles challenges in the literature where vehicle and pedestrian movements are often an afterthought [15], [17].

A joint action can be defined as ''...any form of social interaction whereby two or more individuals coordinate their actions in space and time to bring about a change in the environment'' [33], [47]. The foundation of a joint action is common ground, that is shown to facilitate communication in Fig 2 [33]. An example of a joint action would be considering the physical limitations of another person, such as arm length, when deciding whether to pick up an object that is part of a common goal of moving the objects [49]. Thus, a joint action requires the monitoring and prediction of another person's abilities and actions to complete a common goal [47]. Joint actions interleaved together constitute a joint activity. There are many mechanisms that facilitate joint action but, in general, they rely on shared task understanding, including perception, prediction, and integration of information, or are performed through perception-action couplings such as common (universal) affordances and cognitive simulation of others' actions [50]. These mechanisms link to the biological basis of nonverbal behavior and suggest an intuitiveness for interleaving automated vehicle and pedestrian behaviors. Joint activity theory shows how proxemics, kinesics, and chronemics can be used to send signals, facilitating coordination and helping to accomplish goals.

Joint activity theory distinguishes between instrumental and communicative behaviors—those that achieve goals and those that facilitate coordination [51], [52]. The instrumental aspects of a behavior are those that help accomplish a goal served by the action. For example, if a vehicle is coming to a stop at a four-way intersection, the instrumental behavior includes the deceleration characteristics that allow it to stop safely and comfortably. Communicative aspects of behaviors are the movements beyond the instrumental behaviors, such as exaggerating the deceleration to indicate to other vehicles that it is coming to a stop. These layers of behavior distinguish between actions merely to prevent collisions and those meant to communicate. Therefore, vehicle behaviors such as braking can include communicative aspects to indicate state or intent that can help coordinate actions as part of a joint activity.

Joint activity theory has been operationalized in the human-robot interaction context with robots designed to provide nonverbal cues through gaze, or provide information to repair common ground during an interaction [48]. In addition, it shows that anticipatory behaviors, such as moving a robot arm to the next part that is needed, lead to more efficient time to complete a task and more positive ratings from the users about the commitment of the robot to the task [53], [54]. In addition, these types of nonverbal behaviors improve the robustness to errors by conveying task information [55]. Even if vehicle automation movements are redundant with other signals, this suggests that they will improve performance. Additional cues may be designed to indicate future actions and prepare other road users for interactions. In these scenarios, the robots use models of the person and task being performed—common ground about task characteristics—to accomplish the goal.

Action modulation and goal knowledge can be used in combination to facilitate coordination in a variety of task contexts. However, coordination can be difficult because it requires the ability to predict someones behavior and adjust ones own based on those predictions [33]. The additional effort needed to coordinate is known as the coordination costs [34]. One way to minimize the coordination costs is to use common ground to aid coordination, such as familiar response patterns or using action modulation to convey task information. Tools to minimize coordination costs are coordination devices [33], coordination smoothers [56], and sensorimotor communication [52]. Definitions and examples of these are shown in Fig. 4 and Table 1. In general, these tools rely on considering the knowledge and goals of another person during an interaction to determine the type of information that needs to be transmitted; this can be accomplished

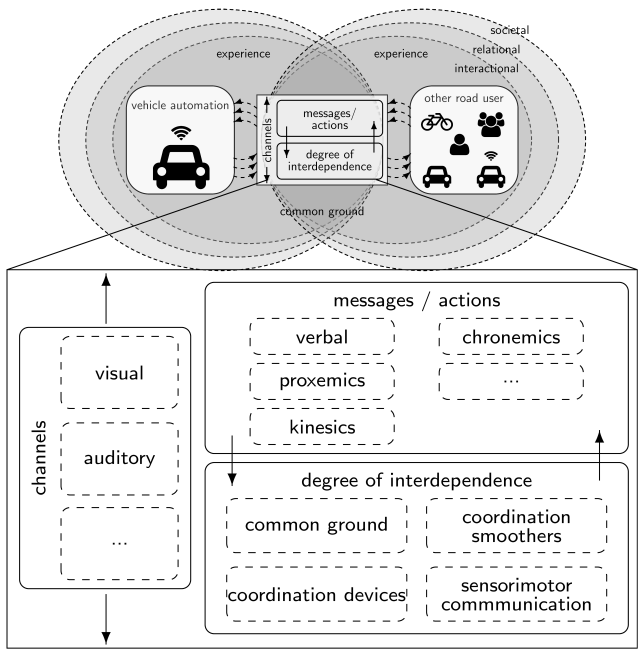

FIGURE 4. Summary of the components of interdependent communication.

TABLE 1. Descriptions of coordination devices, coordination smoothers, and sensorimotor communication.

Communication Tool		Definition	Shared Goal	Example
Coordination Device	Agreement	Explicit communication of intentions	Yes	A hand wave from a driver as an indicator for a pedestrian to cross the road
	Convention	Rules and regulations to less formal codes	Yes	In the U.S., if two people arrive at a four-way stop concurrently, the person on the right can go first
	Precedent	A convention that is developed within the ongoing experience	Yes	Pedestrian following another pedestrian while crossing the road; it is assumed that the right-of-way of the first pedestrian gets applied to the second
	Salience	The next action becomes apparent through the emergence of an affordance in the interaction	Yes	A driver allowing another vehicle to enter by leaving a gap
Coordination Smoother		Reductions in action variability or choices of low variability actions when information about another's goals is not available	No	A coordination smoother designed into vehicle automation would increase its predictability of motion, such as a linear deceleration toward a stop
Sensorimotor Communication		Movement to convey task-relevant information from a person who has access to the information	Yes	Sensorimotor communication designed into vehicle automation would increase its legibility of motion, such as when negotiating a crosswalk where right-of-way is unclear

by reducing action variability, exaggerating an action trajectory, or choosing a specific control action [57]. All of these serve to improve joint action through information exchange.

Sensorimotor communication is effective when one interaction partner does not have a task representation or does not understand the task goal [52], [58], [59]. Sensorimotor communication can further be broken down into ''legibility'' and ''predictability,'' which distinguish the communication objectives of robot movement [59]. Legible motion makes it easy to infer the goal of the robot. Predictable motion makes it easy to anticipate the movement, given a goal. Following this distinction, an exaggerated movement makes it legible, whereas a linear movement toward an specific object makes it predictable. In other words, it may be easy to detect that a vehicle will stop at an intersection based on its trajectory, but if it exaggerates its stop, it may be easier for the pedestrian to determine that it intends to stop. These studies show that automation can communicate and coordinate through movement and those signals can convey specific information about its goals.

Joint action research provides a strong theoretical basis for describing how people coordinate through movement. However, many of these concepts have not been tested in human-automation interaction environments. Although studies show how interactions with humans are different than interactions with robots [60]–[62], it is likely that the presence of mixed traffic, ambiguity of who the driver is, and short time scale of interaction will yield human-like interactions. Indeed, other studies show that people treat computers similar to machines in automatized contexts [63], such as well-practiced crosswalk negotiation [64]. Thus, we find that the joint action research on motion should be extended to characterize other contexts, such as vehicle-other road user communication, where it could be used to reduce the ambiguity of communication signals.

V. EXISTING ROAD USER COMMUNICATION

Much of the existing literature on communication among road users comes from the perspectives of psychology or infrastructure rather than from the vehicle control perspective [65]. One theme that emerges from this literature is peoples' innate ability to evaluate time-to-collision (henceforth time-to-arrival; TTA) [66]. TTA has been shown to influence drivers' decisions of whether to brake regardless of brake lamp illumination [67]. Given the strength of this cue, estimated TTA is promising for signaling the state and intent of the vehicle.

A long history of studies show that people use TTA rather than distance gap or other factors [68]–[70]. For example, almost no one crosses between two and four second TTA, about half of people cross between four and five second TTA, and everyone crosses with a nine to ten second TTA [68], [69]. Additional studies have shown that these estimates can be biased by occluding objects [71] and speed [7], [70], [72], [73]. Lower speeds are associated with higher estimates of TTA (i.e., the vehicle will arrive earlier) whereas higher speeds are associated with lower estimates of TTA (i.e., the vehicle will arrive later). Vehicle size can affect these estimates, with larger vehicles being estimated to arrive earlier [74], [75]. These results suggest the importance of estimated TTA to account for the perception of vehicles.

Factors associated with capabilities of other road users have also been identified as affecting crossing decisions, some through estimated TTA and others through decision making [7]. Older adults exemplify both of these tendencies with a diminished ability to estimate TTA but also poorly estimating the speed at which they can cross an intersection, a discrepancy which may create uncomfortable and unsafe situations [72]. Other factors include risk tolerance of different cultures [76], situational urgency [77], [78], traffic flow [7], [73], and pedestrian distraction [73]. Sucha *et al.* [7] show the interdependence of the vehicle, pedestrian, and environment affect outcomes and encourage an approach where pedestrians' need to feel safe and comfortable is taken into account. This maps well to the model of vehicle automation-other road user communication in Fig 2.

TTA, along with the factors that mediate its perception and influence on crossing behavior, provides a starting point for designing vehicle behaviors that capitalize on human perceptual capabilities. For example, maneuvers can be developed that create clear TTA perceptions, such as by placing the onset of braking earlier when the intent is to stop. However, it is important to remember that those maneuvers also affect the rider. TTA may also be used to infer the crossing intent of pedestrians. Much of the focus on vehicle behavior has only been a secondary consideration for vehicle automation, with few studies focusing on it [14], [79], [80]. Given that people are likely to treat vehicle automation similarly to human-driven vehicles, these behaviors should be the starting point for understanding how to design these interactions.

A. ENHANCING COMMUNICATION FOR VEHICLE AUTOMATION

Crossing decisions have been the focus of most traffic engineering literature due to their relationship to safety. Now with vehicle automation, the importance has shifted to understanding the dynamic components for the design of automated vehicles. Most studies focus on either designing external lighting or understanding current behaviors. External lighting interfaces and gestures are forms of explicit signals, where signals are sent with the exclusive purpose of sharing information—only a communicative purpose [55]. Vehicle and pedestrian movement are forms of implicit signals, where the signal is inherent in the action—an instrumental purpose with communicative aspects. Given the variety of studies, it could be beneficial to understand the methods used and how they are related.

Studies that have leveraged current interactions for understanding the requirements for vehicle automation have commented on the variability across cultures [38] as well as within interactions [14], [79]. For example, the use of horns and lights can vary between polite and aggressive depending on the context and culture [38]. Other studies have shown that people use their stopping behavior to communicate, with stopping short of a crosswalk being an indication of yielding to a pedestrian [14], [81]. Risto *et al.* [81] also found that drivers would use their position relative to a 4-way stop intersection to indicate the order that they would proceed—multiple vehicles were frequently in the intersection at the same time while they coordinated their order. Manipulating the deceleration rate of the automation also has effects on pedestrian crossing decisions that are consistent with the TTA literature [68], [69], [80]. Studies that focus on pedestrian behavior have found that head orientation toward a vehicle is indicative of engagement [79], after which looking away is indicative of a crossing decision [82]. Overall, these studies show the primacy of vehicle and pedestrian behaviors in communication and also point to the difficulty of identifying signals that are consistent across cultures, contexts, and interactions.

A complementary literature involves more explicit communication to be added to vehicle automation, such as external lighting. The EU Project CityMobil2 found that in interactions with an automated vehicle, pedestrians wanted external lighting to identify the vehicle as an automated vehicle and as a cue that they were detected, which was confirmed in focus groups [83], [84]. Other studies have found concerns about explicit signal complexity, despite preferring them [80]. Even though people indicate a positive attitude toward the signals, design preferences from pedestrians vary widely with substantial differences in preferred location, modality, and content [16], [80], [83], [85]. While these studies consider designs from the perspective of the user, they do not consider the system level and context effects, such as the alignment of message intent and interpretation from a communication perspective (e.g., see Fig. 3) [39]. Communication signals that are designed without considering specific use cases may not address the issues that arise in specific scenarios, such as scenarios with multiple pedestrians. Ultimately, these recommendations represent design preferences rather than systematic, model-based principles for facilitating joint activities.

Experimental approaches, such as the Wizard-of-Oz method, have been used as an alternative to subjective interviews but vary in how they measure pedestrian behavior. This approach has focused on communicating states and intent over communicating actions to pedestrians [16], [85], [86] (however, see de Clercq and colleagues [15]). Habibovic and colleagues [85] found that an external interface improved ''perceived safety'' when pedestrians encountered the vehicle compared to conventional vehicles. They proposed three intent indicators on a light bar: ''I'm in automated mode'', ''I'm about to yield'' and ''I'm about to start driving''. However, other studies have not shown an effect of external communication on gap acceptance [87] or decision time [88], with results suggesting that people will rely on TTA as the primary cue for crossing. Alternatively, Petzoldt *et al.* [17] found that a single brake lamp on the front of the vehicle increased decision times—indicating either a safety benefit or confusion. These studies suggest that identifying clear metrics that are consistent with the design intent and choosing between alternatives remain important challenges.

Overall, the communication framework can help reconcile the challenges of competing design preferences [16], [80], [83], [85] and the purpose of measures and their relationship to safety [17], [89]. It suggests that understanding current interactions is necessary for developing communication that aids incidental users, regardless of whether it is through lighting or vehicle movement [88]. One example that clearly emphasizes this need is the conflicting account of the role of eye contact for communication [79], [82], [85], [90]. Recent data suggests that seeing inside the vehicle is unlikely until it is within just a few meters, and even then is very difficult due to glare and other factors [90]. Perhaps this best exemplifies the challenge with using subjective reports from pedestrians to design external interfaces: recall can be unreliable due to misattribution and the general tendency to create post-hoc explanations [91], [92]. These suggest that user preferences may not be the best foundation for designing vehicle automation to ensure safety, efficiency, politeness, and fairness [93].

The vehicle automation-incidental user communication framework provides a starting point to reevaluate the significance of these studies and a path forward for determining design solutions. For example, it shows how many of the proposed design solutions (e.g., verbal codes—text) are disconnected from the information codes that are used to make crossing decisions (e.g., nonverbal) [86]. Understanding where nonverbal behaviors are ineffective would be a first step to understanding what information should be added and how it should be represented.

VI. DISCUSSION

This paper provides a vehicle automation-incidental user communication framework that can inform design and evaluation. The central themes of this framework include interdependence of road user behaviors and how action is used as a communication signal. Thus, road users act jointly toward common goals and coordinate in traffic. Although the concepts described here do not invalidate the need for research on lighting and other explicit signals, it suggests that behavior is the basis for on-road communication and that vehicle automation communication designs that incorporate this may be more tolerable than those that do not. Researchers must consider social and communication aspects of vehicle automation and how it they could affect trust, risk perception, acceptance and tolerance [14].

A key theme of this paper is the incidental user who presents unique challenges for designing communication so that the automation is safe, trusted, and tolerated. Vehicle automation must communicate with incidental users in a way that facilitates coordination and efficiency while also giving the impression of politeness and fairness. This can be accomplished by improving how well automation helps people accomplish their tasks [20], [30], as well as group-level effects that characterize a technology's things like trialability or observability by the public [20]. Designs that consider these factors could reduce negative effects by providing a sense of control and transparency [22], [25], which is the goal of observable and directable automation [94]. In general, this means that if vehicle automation makes its intent clear through either vehicle behavior or external lighting, it will be perceived more favorably.

This paper shows that communication theory can be used to inform the design (e.g., through codes, cues, and channels) and evaluation (e.g., through signals, message and process perspectives, and Shannon's fundamental communication questions). One implication of this review is that actions can extend beyond their instrumental purpose to communication—control is communication and also depends on communication. Extending this to roadway encounters, we showed how TTA carries nonverbal information with it that could be used as communication by manipulating vehicle behavior. Specifically, behaviors such as stopping short of a crosswalk can indicate to a pedestrian that they can cross [14]. The primary contribution of this paper is beginning to place "vehicle behavior" in a broader context and link it to communication. Indeed, different behavior patterns or nonverbal codes may differentially influence perceived safety, efficiency, and politeness, leading to differences in tolerance. In addition, these signals are exchanged in a complex interdependent environment where the exchange may greatly influence those outcomes.

Interdependence in communication not only has implications for design but also for evaluation. The process of signals leading to others' actions can generate a sense of control, trust, and negotiation efficiency. It could also lead to challenges for vehicle automation to send a signal, affecting the other road user's actions, and then responding to that behavior. Such situations can lead to iterative responses that highlight particular design considerations. When communication systems are evaluated, this interplay between action and reaction will be important for understanding the overall effects of the vehicle automation. The interaction may be successful not because of good external communication but because the vehicle or pedestrian adapt to the situation [8].

We also discussed the current state of vehicle automation-other road user interaction research. Much of the research relied upon subjective reports and preferences. Additionally, studies that tried to parse how vehicle behavior influenced other road user decisions relied on proxies for crossing decisions, such as detecting deceleration [17], [89]. Finally, the diversity of designs without an underlying framework or motivation makes it difficult to reconcile competing visions for future external communication through lighting because neither the evaluation criteria nor goal are clear [16], [87], [89]. If we are to encourage the design and evaluation of vehicle automation that will generate high levels of acceptance among people, they will need to consider what the desirable outcomes are and how to measure them.

We have provided a framework that identifies vehicle behavior as a critical component to communication. Certainly the foregoing literature suggests that vehicle behavior is a strong signal that cannot be easily circumvented by the addition of external lighting. What may be more productive for designing communication is to consider the vehicle automation interaction as a whole, where vehicle control algorithms and external lighting are not meant to merely replace the driver, but to enhance the interaction.

A. IMPLICATIONS FOR DESIGN & EVALUATION

Given the theoretical support that we have provided for designing communication strategies of vehicle automation, it is necessary to explore how they could be applied. In general, we take the view of Becchio *et al.* [95] who suggest a process for "seeing mental states." People observing the states of automated vehicles is not part of their approach; however, the proposed procedure can be applied to those situations. Their approach is a four step process:

1) Quantify available intention information (e.g., features of the vehicle or pedestrian trajectories);
2) Determine the perceptual efficiency of the information (i.e., are agents able to observe those features?);
3) Identify features that observers use (i.e., which features are used to make decisions);
4) Model the observability of intentions (e.g., systematically manipulate the most important features in an experiment).

This process leads to interactions that are grounded in human perception while also identifying challenges that may be resolved through additional signaling mechanisms. A key to this approach is the "observability" of mental states, or in our case, complex automation states and intentions.

Automation "observability" has a history in the human-automation teaming and coactive design literature and is typically paired with "directability" and "predictability"—features of automation design that are intended to improve performance [35], [94]. A central theme to coactive design is designing for interdependence, or the degree to which ones actions' outcomes depend on the actions of others. Higher degrees of interdependence require more coordination to accomplish joint goals. For human-automation interactions this can be aided by creating automation that is observable, directable, and predictable [35]. Observability can be described as the ability to know the automation's current state. Directability can be described as the ability to influence the automation's future state. And predictability can be described as the ability to know the automation's future state. In this sense, Becchio and colleagues' modeling of observability [95] could be expanded to include directability, and predictability of others given different time horizons. Thus, this method provides a way design the interpretability of agent intentions and states.

We can further break the design of vehicle automation into distinct parts. Design elements (Fig. 5) constitute

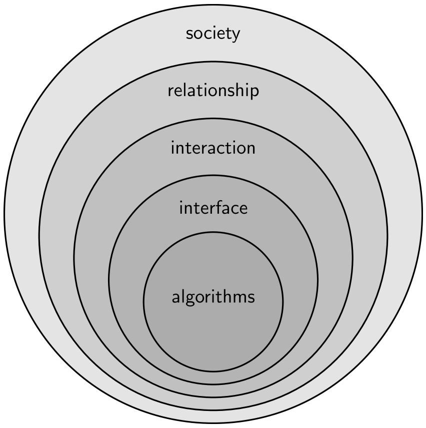

FIGURE 5. Layers of design elements for vehicle automation-incidental user communication.

design choices which could manifest as communication to incidental users. Algorithms control system states such as braking or accelerating—the behaviors performed for their instrumental purpose. The interface is the displays and controls available to the people interacting with the technology. In the case of incidental users, the interface can be the communicative behavior beyond the instrumental purpose of stopping, such as proxemics, kinesics, or chronemics. Additionally, it could be the addition of lighting to aid the interaction with other road users. Interactions are how the algorithms and interfaces are invoked and adjusted based on the interdependencies with people; for example, mechanisms for coordination could aid the interaction. Interactions characterize the how, when, and where of algorithms—the changes in the algorithm over time depending on the environment. The relationship characterizes the experience of an incidental user over time which influences their trust, perceived risk, tolerance, and acceptance. The relationship constitutes the accumulation of experiences and may include more than just an individual vehicle interaction; this is what enhances or inhibits the diffusion of the technology. Finally, society includes the rules, norms, and cultural aspects that influence the interaction, such as preferences for aggressiveness of vehicle automation. These elements correspond to aspects of the transactional model of communication (i.e., Fig. 2).

Habibovic *et al.* [85] present a study that can be used as an example of how to apply the framework presented in this paper along with the process proposed by Becchio *et al.* [95]. They present a system where an LED strip at the top of the windshield expands or contracts depending on the acceleration or deceleration of the vehicle. There are some questions that we might ask to explore how the system improves communication between vehicle automation and other road users:

1) Where does the the intention information come from (e.g., interface, algorithms, or interaction)?
2) What is the perceptual efficiency (e.g., how does the pedestrian decode the information)? In other words, to what extent do the LED patterns improve an understanding of intention or state? And does the pedestrian look at and use this additional information? If not, what are other advantages of redundant information?
3) How can we identify what information is used and in what contexts? How can we manipulate these variables to understand a pedestrian's interpretation of the vehicle's intention or state?
4) How can we model the observability of intentions (e.g., systematically manipulate the most important features in an experiment)?

One aspect to manipulate are the nonverbal codes of proxemics, kinesics, and chronemics to see if an aspect of vehicle behavior affects outcomes. In tandem, we may manipulate characteristics of the LED strip to enhance desirable effects or diminish undesirable ones. There are many details in this example omitted for brevity; however, we believe it provides a sense for the advantages of a more systematic and theoretically-grounded approach to vehicle automation-other road user communication.

B. CONCLUSION

This paper provided an overall communication framework to consider for the development of vehicle automation-other road user interactions. The implications are clear: for vehicle automation-other road user communication to be effective, it will need to consider communication through vehicle behavior as well as potential signals to be added to the vehicle to enhance communication.

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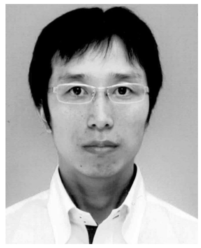

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