Entanglements and Unintended Consequences of Automated Vehicles: An Instance-based Discussion for Generative Uncertainty

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Figure 1: Overview of instances of unusual AV interactions. Image generated using ChatGPT 5.2

Abstract

Automated vehicles (AVs) are moving from speculation to real-world implementation, revealing the true effects of this technology beyond theoretical expectations. While AVs are delivering on some of their promised benefits, their deployment has also introduced unintended consequences. We illustrate this dynamic through six real-world examples from current AV implementations, demonstrating how the application of this technology has become entangled in complex dynamics. We argue for the implementation of human-computer interaction and design-based techniques to proactively explore the consequences of AVs, to complement the use of reductionistic scientific approaches. We propose embracing generative uncertainty, which means treating uncertainty as a source of inspiration and exploration, to serve as an open-ended approach for engaging with potential consequences. To address unintended consequences of AVs, we discuss extensibility and increasing AV comprehension as current opportunities and highlight future envisioning and tools for managing uncertainties as two complementary approaches for leveraging generative uncertainty.

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• **Human-centered computing → Interaction design**.

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1 Introduction

Automated vehicles (AVs) have promised to bring many positive consequences to society, such as enhanced safety, ride-sharing and less traffic congestion [15]. Since AVs are already allowed on some roads, the actual consequences of AV deployment can also be reflected upon, as is done by Waymo. In their Safety Impact analysis based on actual AV performance, the company reports fewer crashes compared to the average human driver [1], and on their Sustainability page CO_2 reductions and the usage of connections with public transport are highlighted as well [2]. This positive match between foreseen and reported consequences implies AVs' positive impact. However, next to achieving the foreseen positive consequences, AVs also lead to unintended negative consequences.

As the popular saying goes: "If you always do what you've always done, you'll always get what you've always got". While practicing what has been done before can lead to predictable and stable outcomes, practices that deviate can lead to more uncertain and unintended outcomes. This applies to design activities as well, where more novel designs have more potential for unintended consequences [27]. In the context of design, Walsh et al. [27] defined the phenomenon of unintended consequences as "the difference between intended and actual system behavior", which highlights "the intended behavior is considered from the perspective of designers, decision makers, or policymakers".

This notion of innovation leading to unintended consequences is further illustrated in the book *Why things bite back* [25, p. 144]. It describes how the early adoption of automobiles (ironically) spread the Tribulus terrestris, an until then rarely speciated puncture vine, whose seeds punctured vehicle tires. As Tomitsch and Baty [26] note, seemingly small decisions can have big unintended consequences, and draw a parallel with the famous butterfly effect.

Similarly, the large-scale adoption of novel AVs may lead to unintended consequences. Notably, increases in ownership and the decrease in the use of public transport could be an unintended consequence, which potentially can increase congestion [18, 19]. In the domain of AV interaction, potential negative consequences are also foreseen in how AVs interact with their environment. For instance, researchers considered that AVs' communication with other road users (ORUs) might be different due to the lack of a driver [13, 16]. To address this issue, a large variety of external human-machine interfaces (eHMIs) have been developed. However, studies with eHMIs are often conducted under predefined lighting, road setups and traffic conditions, as noted by Dey et al. [7]. A similar methodological orientation in AV research was noted by Dong et al. [8], who describe that studies in the field of AV HMIs often focus separately on either in-vehicle interaction or external communication between AVs and ORUs. Studies focusing on specific groups or conditions apply a reductionistic approach, which tames and disciplines external uncertainties and aims to solve clearly defined problems, for example, by isolating one variable and then researching the effect of such a variable [10]. While this approach functions well to solve clearly defined problems and to understand the effect of one variable in a specific setting, in real-life settings, design practices contain multiple intertwined factors. Especially in the case of traffic, designs do not function in isolation but need to operate in complex and unique contexts. This has been noted in mobility research, leading to increased attention to a more holistic perspective on HMIs that accounts for the complexities of different user roles and the experiential elements of AV interactions [5, 8, 9, 11]. In doing so, these methods reintroduce complexities and uncertainties that are typically controlled in reductionist approaches.

In contrast to reductionistic approaches, and in line with this previous work, we argue to further advance the perspective in AV interaction research to not merely see uncertainties as something to be disciplined. This stance can leverage uncertainties in an open-ended manner to better address complex and intertwined interactions that AVs need to deal with. Therefore, we propose the usage of uncertainties for generative purposes [10]. This view on uncertainty was introduced in the field of human-computer interaction as one of the four modes of viewing uncertainty Soden et al. [23], together with the three other modes of (1) disciplining uncertainty, (2) uncertainty as (psychological) affect, and (3) politics of uncertainty. The framing of treating uncertainty as a generative resource resonates with foundational understandings of design problems as "wicked" and that there are "no definitive conditions or limits" [6] and that it is unlikely to be fully specified in advance [24]. Design practices are fundamentally indeterminate, and to a large extent about handling the complexity [24]. Designers, therefore, must aim to surrender to uncertainties and use these as generative resources to both uncover and reopen previously set in stone solutions [10].

1.1 Aim of this publication

The key contribution of this publication lies in (1) illustrating how unintended consequences emerge from AV deployments through real-world instances, and (2) framing generative uncertainty as a resource for those who design, develop, engineer, or otherwise contribute to the development of AVs to proactively explore consequences beyond reductionistic testing approaches.

2 Unintended consequences of AV technology: practice-based exemplification

Through real-world exemplifications, this paper will illustrate how the implementation of AVs can lead to interactions in unintended and entangled ways. To illustrate this notion of influence, we discuss practice-based instances from current AV implementations from both Tesla and Waymo, which are actively driving their AVs in some states as ride-hailing services. Waymo has been expanding its services through multiple cities in the past 5 years and currently does 250,000 trips per week [3]. Tesla launched its Robotaxi service in the summer of 2025. Although the service is provided in both Austin and the Bay Area, only 34 vehicles in Austin, Texas, operate without safety drivers [4].

[1] https://waymo.com/safety/impact/
[2] https://waymo.com/sustainability/
[3] https://waymo.com/intl/zh-tw/about/#blog and https://waymo.com/sustainability
[4] https://www.jalopnik.com/2063124/tesla-austin-robotaxi-fleet-34-cars

The instances reported below were collected by the authors through engagement with public discourse, including news reporting and social media. The selection was based on common agreement between the first and second authors regarding the fit of unintended consequences as defined in this paper. The instances serve as illustrative exemplars that demonstrate the presence and diversity of unintended consequences in current AV deployments.

2.0.1 Instance 1: A loud parking lot. After an update issued by Waymo, a parking lot in San Francisco, California, was filled with honking sounds. Located in front of apartment buildings, the lot was reserved for Waymo vehicles. Waymo stated the update intended to prevent collisions. Ironically enough, another update issued by Waymo stopped their vehicles from honking in the parking lot, but led to the unintended consequence of bringing their vehicles to an adjacent cul-de-sac where they would then repeatedly honk. This instance is based on the reports of [12, 22].

2.0.2 Instance 2: Controlled by clothing. AVs can be controlled by the clothing we wear in unintended ways. To adhere to traffic laws, AVs are designed to detect traffic signs. However, a demonstration on social media shows that a traffic sign printed on a t-shirt can lead to an AV detecting this “sign” and interpreting it as a real traffic sign. A follow-up test demonstrated how, in three out of the four scenarios, the Waymo responded to the stop sign printed on the T-shirt by coming to a full stop. The original social media demonstrations were done by Carr and reported by Carscoops [4].

2.0.3 Instance 3: Caught in political fire. During protests against President Donald Trump's immigration crackdown in downtown Los Angeles, California, five Waymo vehicles that were present in the area were vandalized, set on fire and were not able to be retrieved [20]. Photos show how multiple vehicles, covered in anti-ICE graffiti, were burning out on the road.

2.0.4 Instance 4: Stress testing the Robotaxi. In a Tesla Robotaxi, a YouTuber decided to purposefully test for unforeseen and unsolved interactions. Not only did the YouTuber open the unlocked door to the ‘driver place’, he also rolled down the windows after the drop-off had been done, leading the Robotaxi to drive away with the windows open. Among other things, he tried falling asleep to see if and how he would be woken up, and intentionally left luggage in front of the AV to see if the front cameras would detect it [2].

2.0.5 Instance 5: A Physical Waymo DDoS Attack. Self-described tech prankster and software engineer Riley Walz organized 50 people at dusk to order a Waymo simultaneously, named after the Distributed Denial of Service (DDoS) attack from IT where coordinated online traffic aims to overload a service. Photos show the street flooded with empty Waymo vehicles, which reportedly waited on the street for around 10 minutes, since no one boarded the vehicles [3].

2.0.6 Instance 6: Waymo driving into police standoff on the street. Multiple police vehicles had stopped in Los Angeles, California, to conduct a high-risk felony arrest. While the suspect was lying on the road during a standoff with the police, a Waymo took a left turn and drove closely to the standoff, leading bystanders to say “Oh my god, what the F— is that Waymo doing?” After the Waymo was out of sight, a group of police officers with pulled weapons approached the suspect. This incident was reported by the media in 2025 [1].

3 Entanglements and unintended consequences

Beyond the scope of the continuous coordination that is needed for AVs to navigate the road with others [21], we consider that AVs need better handling of the systemic complexities they encounter. The above instances illustrate how AVs become entangled in political demonstrations and how their systems are intentionally misused and misled. Although some situations involve intentional actions by bystanders, the outcome still can be seen as unintended consequences, as they are defined by the expectations of designers, decision makers, and policymakers [27].

With the expanding application of AVs, the effects of unintended consequences may increase. Due to similar behavior, a change in software can influence many AVs, as could be seen in instance 1, where a new software update by Waymo led to many Waymos honking in their parking depot at one another. Furthermore, as AVs will start driving in new operational design domains (e.g., new cities, countries or continents), they will encounter new environments, behaviors and socio-cultural norms which may lead to different consequences.

4 Opportunities for dealing with systemic complexities

4.1 Extensibility

Particularly for AVs, manufacturers should continue their efforts in making solutions in such a way that they remain adaptable down the road (e.g., through software). In this way, software and/or hardware updates remain an option to adapt AVs to unintended consequences. Positioning this in the context of current AV applications, Waymo indicates learning and updating their software based on current events [1, 12].

Keeping products extensible to be able to learn from past events and make changes in times of unintended consequences is not sufficient to address complex entanglements. Because failures in automated vehicles can have safety-critical consequences, learning must be proactive as well: waiting for errors to occur before learning from them is irresponsible. Therefore, we consider that extensibility is necessary but does not replace proactive exploration using generative uncertainties.

4.2 Increasing AV comprehension

Another opportunity for AVs to better navigate complex situations and entanglements lies in further increasing the AVs' comprehension of situations. In this way, AVs could better detect complex entanglements and unintended consequences. One way to approach this is with improvements in AI models (e.g., large language models), which can be leveraged for their ability to use language-guided reasoning and world-knowledge [14]. Notably, increasing AI complexity and comprehension can also lead to the creation of new unintended consequences due to two reasons. Firstly, growing complexity in AI models now can lead to models so complex that their way of functioning becomes unclear even to their creators. Secondly, as these models would be trained on existing data, we should remain cautious to give all responsibility to such systems for handling unintended consequences with novel technologies.

5 Approaches for leveraging generative uncertainties

As demonstrated by the six instances, current AV deployments interact with their environments in complex and entangled ways, resulting in unintended consequences that extend beyond what can be anticipated through reductionistic testing alone. We therefore argue that AV development should be complemented with an open-ended approach that explicitly treats uncertainty as a generative resource. While such an approach cannot predict or prevent specific incidents such as the instances above, systematically engaging with generative uncertainty can support anticipating broader classes of unintended consequences before deployment. Building on this argument, the following section outlines two starting points that illustrate how generative uncertainty can be incorporated into AV research and design practices.

The first is to leverage generative uncertainty for exploring potential futures of AV interaction. We draw on the anticipatory approach proposed by Moesgen et al. [17], which contains three phases: (1) Envisioning possible futures, (2) Concretizing futures in a user study and (3) Interpreting findings and projecting implications to better-informed futures. They extend the human-computer interaction toolkit towards exploring alternative futures with generative uncertainties. In the first phase, inspiration for scenario development could be based on open questions, trends, and future concepts for AV designs. Through applying the STEEPLE (social, technological, economic, environmental, political, legal, and ethical factors) factors [17], a holistic understanding of multiple possible, plausible and probable scenarios in which their AV might need to operate could be formulated, thereby expanding the design space beyond predefined scenarios. In the second step, an immersive user study might test a selection of the scenarios that depict uncertainties from the first phase, in which users enact their behavior and can interact with the AV prototype in their new context. In the third step, findings from the study are projected back into the future and interpreted holistically for their potential impact. Applied to AV interaction, this approach enables moving beyond predefined scenarios and can help reveal how AV interactions are entangled with other factors, where unintended consequences may emerge.

We see a second starting point in the work of Epp et al. [10], which describes tools for designers to further explore (partially) uncovered uncertainties in more detail. More specifically, they discuss three possibilities for exploring generative uncertainties, which are: (1) Deviating widely, (2) Repeated focusing and (3) Oscillating between uncertainties. *Deviating widely* could be applied to deviate from immediate uncertainties surrounding AVs (e.g., related to computer vision or route planning) to unknown territory (e.g., exploring all potential roles AVs can play in public space), to discover new, unperceived uncertainties. In the context of AV design, *repeated focusing* could involve continuously revisiting a complex uncertainty, such as potential ways of misuse. This process can reveal smaller, related uncertainties that may otherwise remain unperceived (e.g., new subcategories of uncertainties of misuse). Finally, *Oscillating between the Uncertainties* can mean freely moving between an overview of uncertainties and using them as vantage points to further explore or understand another uncertainty. When faced with uncertainties during the AV development process, these three possible tools can be leveraged to further uncover and position uncertainties.

6 Discussion and future work

We aim to provoke those involved in AV development to complement reductionist approaches with a more open-ended one that leverages uncertainty as a generative resource. Such an approach can better account for the complex entanglements that AVs encounter in practice. Using six instances, we exemplify how unintended consequences emerge in current AV deployments, which demonstrate the complex entanglements that AVs need to cope with. To address this, we discussed opportunities that could help mitigate unintended consequences. We argued that, complementary to those opportunities, generative uncertainty should also be used for proactive exploration. We advocate applying the anticipatory design approach of Moesgen et al. [17] to explore future AV applications, alongside the tools proposed by Epp et al. [10] to further uncover and deepen the understanding of existing uncertainties.

Given the US-centric nature of the instances, they are not presented as a representative sample. Instead, consistent with the generative approach of this work, they illustrate only a subset of the complex and entangled situations that may emerge. Future research should therefore undertake a more systematic examination of instances across more diverse contexts to deepen the understanding of AV entanglements. Moreover, the methodological integration of generative uncertainty in AV design requires further development, followed by empirical evaluations of its effectiveness in development and testing contexts. As explored uncertainties may evolve over time, AVs will need to adapt their behavior as conditions change, thereby requiring longitudinal research and continuous development.

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