Will Weather Dampen Self-Driving Vehicles?

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ABSTRACT: Innovative technologies that support implementation of automated vehicles continue to develop at a rapid pace. These advances strive to increase efficiency and safety throughout the global transportation network. One important challenge to these emergent technologies that remains underappreciated is how the vehicles will perform in adverse weather. Each year, weather-related vehicular crashes account for approximately 21% of all highway crashes in the United States. These crashes result in over 5,300 fatalities, injure over 418,000 people, and cost billions of dollars in insurance claims, liability, emergency services, congestion delays, rehabilitation, and environmental damage annually. Automated vehicles have the potential to significantly mitigate these statistics; however, public, private, and academic partnerships between the meteorological and transportation communities must be established to develop solutions to weather impacts now. To date, such interactions have been sparse and largely contribute to a lack of awareness in how these two communities may collaborate together. The purpose of this manuscript is to call the meteorological community to action and proactive engagement with the transportation community. A secondary goal is to make the transportation community aware of the advantages of teaming with the weather enterprise. Automated vehicles will not only increase travel safety, but also have benefits to the meteorological community through increasing availability of high-resolution surface data observations. The future challenges of these emergent technologies in the context of road weather implications focus on vehicle situational awareness and technological sensing capability in all weather conditions, and transforming how drivers and vehicles are informed of weather threats beyond sensing capabilities.

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The world presently sits at the precipice of a transportation revolution in the fifth epoch of high technology (Borchert 1967). Automated vehicles (AVs), along with their associated technology such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications (Fig. 1), present significant promise to promote enhanced safety and efficiency throughout the global surface transportation network. The U.S. Department of Transportation (USDOT) Intelligent Transportation Systems (ITS) Joint Program Office (JPO) defines connected vehicles (ITS JPO 2020a) as vehicles with electronic communication capability such as V2V, V2I, and vehicle-to-everything (V2X) communications. These communications may use dedicated short-range communication (DSRC) or cellular technology. Connected vehicles still require a human driver to operate; however, they receive information about their environment in support of driver operation. This information may include vehicle speeds, trajectories, signal timing, work zones, lane closures, brake status, and more.

AVs (ITS JPO 2019a, 2020b) refer to vehicles in which some or all aspects of operation are controlled by the vehicle itself with or without contribution from a human driver. Traditional examples of AV operation includes cruise control capabilities. More modern examples of automation include lane-keeping and automatic parking assistance features. AVs may be autonomous (i.e., use only vehicle sensors) and may also be connected (i.e., use communications systems such as connected vehicle technology, in which cars, roadside infrastructure, and remote data centers communicate wirelessly; Fig. 1). For further reading on recent advancements in connected and automated vehicles, the interested reader is directed to Elliott et al. (2019).

The USDOT National Highway Traffic Safety Administration (NHTSA) defines five levels of automation with respect to AVs (NHTSA 2019a). Level 1, also referred to as driver assistance, is where a vehicle is controlled by a human driver, though some assist features (e.g., lane departure alerts) are included in vehicle design. Level 2, partial automation, is where a

Fig. 1. Connected vehicles are those that communicate with nearby vehicles and fixed infrastructure such as traffic signals, though they are not automated and require a human driver to operate. Automated vehicles are those that operate in isolation from other vehicles using onboard sensor fusion. Connected automated vehicles leverage the capabilities of both technologies.

vehicle has a combination of automated functions such as accelerating, braking, and steering, though a human driver must remain engaged at all times. Level 3, conditional automation, does not require a human driver to be continuously engaged but rather ready to take control of the vehicle at times with notice. Level 4, high automation, is where the vehicle is capable of performing all driving functions under optimal conditions, though a human driver may still have the option to manually control the vehicle. Last, level 5, full automation, is where the vehicle can perform driving functions under all conditions and a human driver may or may not have the option to manually control the vehicle. Conditional automation (level 3) and beyond are likely where the most significant and complicating weather considerations will need to be addressed, especially in the context of defining the limits of conditions for safe, autonomous operation.

AVs present profound challenges and opportunities in the context of weather. The fundamental challenge is AVs' ability to operate safely in all weather conditions given the prospect that they may be unable to sense or react to the driving environment under the full range of weather and road pavement conditions. Successfully overcoming this challenge, however, yields significant opportunities if AVs can safely react to, sense, and collect weather and road condition data and then provide useful information to users. Further, the benefits of safe and reliable adverse weather AV operation can contribute to lowering the present cost of weather-related vehicular crashes. During 2007–16, weather-related vehicular crashes accounted for 21% (1,235,145) of all reported crashes annually (Fig. 2) resulting in 16% (5,376) of crash fatalities and 19% (418,005) of crash injuries throughout the United States [Road Weather Management Program (RWMP); RWMP 2019]. The total economic and societal cost of all vehicular crashes in the United States was estimated at \$836 billion in 2010 by NHTSA (Blincoe et al. 2015; NHTSA 2019b). This amount includes \$242 billion in maintenance and congestion costs and \$594 billion from injuries and loss of life. Considering the relative percentage of weather-related crashes, they account for approximately \$180 billion annually.

Current practices in addressing weather-related transportation network challenges include 1) advisory, 2) control, and 3) treatment strategies [Federal Highway Administration (FHWA); FHWA 2019a]. Advisory strategies leverage telecommunications resources and dynamic variable message signs to inform motorists of conditions and additional resources. Control strategies restrict access to roadways during particularly hazardous conditions, in addition to modifying traffic flow rates through means such as signal timings. Treatment strategies involve physical and chemical maintenance operations activities designed to mitigate the impacts of weather conditions on roadways, primarily during winter weather. Private companies and public transportation agencies invest significant resources to obtain accurate real-time and forecast weather and road condition information to ensure efficient supply chain management routing and traffic management (FHWA 2019b). Public transportation agencies exhaust further resources to mitigate the impacts of hazardous weather on roadways. Winter road maintenance

Fig. 2. Vehicular crashes that occurred under adverse weather conditions in the United States from 2007 to 2016 (RWMP 2019). It is important to note that additional factors such as rain, snow, and fog are not disaggregated from pavement conditions in this graphic. The percentage due to fog is for those crashes that occur under foggy conditions, but not wet, icy, or snowy pavement conditions.

operations (e.g., plowing roads, chemical deicing applications) account for approximately 20% of state departments of transportation (DOTs) annual maintenance budgets (RWMP 2019).

In 2004, the Transportation Research Board (TRB) and National Research Council (NRC) published a comprehensive study as a response to the growing recognition of weather's significant impact on roadway safety and capacity (NRC 2004). This previous study was the most comprehensive assessment of road weather and related services and served as the first roadmap for improving delivery of weather-related information to the nation's transportation network. In recent years, the field of road weather research, forecasting, and operations has evolved further into its own highly specialized area of expertise. In the academic sector, past studies have developed road pavement temperature and prediction capabilities (Crevier and Delage 2001; Siems-Anderson et al. 2017), considered social science implications of road weather hazard risk communication (Drobot et al. 2014), assessed historical climatology and spatial distribution of weather-related crashes (Black and Mote 2015), and quantified weather impacts for DOT operations (Walker et al. 2019). Increased availability of robust and trustworthy weather information and forecasting has improved the efficiency, effectiveness, and cost-savings of winter maintenance operations (Strong and Shi 2008; Ye et al. 2009). Today, due to the benefit of weather information and the successful transfer of academic research to operational practices, impact-based data and forecasts are commonly used by many transportation agencies. At the same time, the technologies used to observe and forecast the roadway surface environment are being rapidly developed and constantly improved. Access to wireless communications has meant that observations collected from sensors on vehicles can now become foundational for many agencies. Mobile-based data also feed into software that provides maintenance decision support in real time to a variety of end users, from traffic operations staff to snowplow operators (Shi and Fu 2018).

Innovation is not isolated to mobile technologies though. Numerical weather prediction used by human forecasters is constantly improving, and traditional weather station installations continue to push the boundaries of what can be observed and how those observations can be used in intelligent ways to support many transportation agency activities (Shi and Fu 2018). Today, the rapid advancement of AVs represent the next grand challenge for road weather services. These advancements come at the same time as aging transportation infrastructure is seeing historic impacts from extreme, often unprecedented weather events. The next generation advancements in road weather technology are upon us and will be critical to the success of AVs.

As alluded to above, the road weather industry has been growing and maturing for about two decades, while AV as a field is relatively new. Current federal regulations and guidance from the USDOT and the White House Office of Science and Technology Policy concerning the implementation of AVs do not explicitly include weather (USDOT 2019). The regulatory and policy guidance direct the USDOT, acting as a convener and facilitator across all sectors, which research and development activities should be conducted to ensure international leadership with respect to AV implementation. This lack of explicit focus on weather challenges discourages broader research and development efforts to overcome a looming challenge. Further, barriers to implementation and adoption of AVs include past non-weather-related setbacks including a collision of an Uber automated vehicle with a pedestrian in Arizona (Griggs and Wakabayashi 2018) and a fatal crash of an automated Tesla in Florida [National Transportation Safety Board (NTSB); NTSB 2017]. Additional barriers include challenges such as rural versus urban environments, gaps in information, communication, security, and reliance of the current technology primarily on pavement markings. While there is substantial research on these topics and the ethical dilemmas of AVs (Bonnefon et al. 2016; Awad et al. 2018; Maxmen 2018), there is much less on understanding and improving how AVs will behave in all weather conditions.

Weather primarily impacts the surface transportation network in two fundamental ways: 1) impairment to situational awareness, including visibility, and 2) inhibitions to vehicular maneuverability (RWMP 2019). Poor visibility conditions resulting from heavy precipitation, blowing dust or snow, and dense fog can result in multivehicle crashes as drivers become unaware of their position, location, and speed relative to adjacent vehicles. Wet, icy, slushy, and snow-covered pavement reduce friction and result in loss of vehicle control. AVs must be able to accommodate both implications presented by weather conditions.

The American Meteorological Society (AMS) Intelligent Transportation Systems and Surface Transportation Committee (ITS/STC) and its Mobile Observations Subcommittee serve under the AMS Board on Enterprise Economic Development and the Commission on the Weather, Water, and Climate Enterprise (CWWCE). The AMS ITS/STC seeks to foster broad cross-disciplinary collaboration to promote the safe and reliable implementation of AVs. This article will discuss the readiness levels of, and barriers for, both the meteorological and AV communities for research and development collaborations to enhance the capabilities of AVs in adverse weather.

Is the AMS community ready for self-driving cars?

The meteorological community has made technological advancements critical to AVs. These range from advancements in remote sensing and numerical weather prediction [National Oceanic and Atmospheric Administration (NOAA); NOAA 2019], to the National Weather Service (NWS) shift to impact-based decision support services and hazard simplification (NWS 2020). Despite such advancements, a fundamental remaining challenge to AVs in adverse weather is the communication of critical weather information. While an existing NWS directive clarifies the roles and responsibilities of the NWS with respect to surface transportation interests (NWS 2019), additional situations involving AVs may provide further complexity. In the current directive, NWS may collaborate with and provide general weather information to transportation agencies and their private weather enterprise partners, primarily to ensure consistency in public-facing communications and forecasts. NWS is restricted in its ability to provide transportation agencies or users with site-specific road weather forecasts that include information regarding road pavement temperatures or conditions. This information is reserved for the private weather enterprise providers to disseminate. While this directive may be sufficient for current operations, AVs' weather communication information falls somewhat cross jurisdictional under the NWS, transportation agencies, private weather enterprise, and the automotive manufacturers who are not even considered in the current directive. Will private weather enterprise, NWS, transportation agencies, automotive manufacturers, or some other entity manage the bidirectional data conduit of critical weather information? Will it vary with different weather conditions? For example, your AV entering a tornado or snow-squall warning polygon along an interstate highway is a different situation than your AV entering an area of relatively light precipitation. Furthermore, data privacy, ownership, and acceptable use challenges will need to be addressed. While the AMS community may not be the appropriate venue for data ownership conversations, it is with respect to provisions of weather information to a variety of end users.

In October 2018, the AMS CWWCE organized the inaugural Automated Vehicles and Meteorology Summit held at the National Transportation Safety Board in Washington, D.C. (AMS 2019). The purpose of this event was to bring together transportation and meteorological expertise from all sectors to discuss the critical needs of AVs and their aerial counterparts. Over the course of two days, participants candidly discussed topics ranging from AV sensing platforms, capabilities, and use cases to AV industry perspectives and meteorological needs. This summit was pivotal in gathering all relevant stakeholders to discuss the issues, challenges, and potential solutions for AVs in adverse weather conditions. It also provided a foundation

for future engagement throughout both the meteorological and transportation communities (W. Mahoney 2019, personal communication).

The AMS community has some work to do in order to be ready for self-driving cars. The primary shortcoming of the October 2018 summit was the lack of broad participation from the AV community due to unforeseen scheduling conflicts. Discussions in progress may lead to AMS hosting a follow-up summit by partnering with other organizations in the AV community in a location more amenable to the AV community (e.g., near an AV testing facility). The AMS community is largely unaware of the limitations and challenges facing the AV community due, in large part, to the lack of meaningful interaction between these two communities. Additionally, the proprietary nature of the industry does not lend itself to open, broad collaborations. We do not know what we do not know and, therefore, cannot develop solutions to the unknown. Other partner organizations are beginning to highlight this issue that the AMS community should be a leading authority (Lopatka 2019). Stakeholder summits are a pivotal means to begin more meaningful engagements, though alone these are insufficient. Such summits must produce broad, cross-community research and development solving weather-related AV challenges. To this end, the AMS community must continue to advance its own science while making connections with end users such as the AV community.

Is the AV community ready for weather?

With specific focus on the advent of AVs, the FHWA RWMP has begun research and testing to identify how vehicles will detect and react to adverse road weather conditions (FHWA 2019c). AVs have sensors and perception systems to detect objects and events in their vicinity. Using this information, they control the steering and speed to move the vehicle along its selected path. Their ability to properly perceive the situation and execute a maneuver can be affected by road weather. Perception of an environment for automated driving requires two main sets of information: the type of objects around the vehicle and the position and velocity of those objects (FHWA 2019c). A wide variety of different means are available to achieve this objective, but most commonly control is achieved using a combination of cameras and radar sensors (FHWA 2019c). Most AVs use cameras in conjunction with machine vision algorithms to identify objects and markings on the roadway. Some use multiple cameras to add depth perception, through stereo vision. Radar detects objects by measuring the return of electromagnetic radiation, which for automotive applications is generally 77 GHz (W band). Two testing periods have occurred with three AVs each in 2018 and 2019 (FHWA 2019c). All AV models used for these tests were commercially available in the United States, though due to legal constraints the specific models cannot be disclosed in this manuscript. All had machine vision (one or more video cameras), and two had a radar. The AVs selected for these tests strictly relied upon onboard technologies, video, and radar. The tests conducted were developed with the intent to challenge perception systems across a variety of simulated adverse weather conditions in a controlled outdoor laboratory setting. Production vehicles with different perception systems were driven through a planned variety of road weather conditions to permit an assessment of how well the automation features of each AV performed. The results from these tests provided data to FHWA and other stakeholders on how selected perception systems performed in a limited set of adverse weather conditions. Key findings indicate that AVs had the greatest difficulty with heavy precipitation regardless of precipitation type, variable amounts of roadway snow cover, and sun glare overwhelming optical sensors on the vehicles. In all scenarios, AV performance improved when following another vehicle operated by a human driver compared to traveling through various conditions with complete reliance on vehicle sensors. More detailed results are available in the complete FHWA report (FHWA 2019c). Additional testing will be conducted during 2020 and 2021. Working with stakeholders to create scenarios, this testing will occur with AV sensor and perception

systems with different levels of automation under certain adverse weather conditions (e.g., fog, mist, smoke, wind gusts, winter weather conditions). These tests will be both simulated and naturally occurring, as weather permits, in diverse traffic situations.

While the potential of AVs remains uncertain, connected vehicles (CVs) have carried forward many mobile data advancements relevant to the meteorological community. In 2015, USDOT awarded federal grants to three pilot sites with the aim of deploying the CVs that have been in active research and development for the past decade [ITS JPO 2019b,c; NYC DOT 2019; Tampa Hillsborough Expressway Authority (THEA); THEA 2019; USDOT 2019]. The Wyoming DOT (WYDOT) site (Fig. 3) has built applications around CV technology along the Interstate 80 (I-80) corridor to provide critical safety and weather information to commercial motor vehicles (CMV) as they move freight across the state (Siems-Anderson et al. 2017; Welch et al. 2017; WYDOT 2017; Ragan and Siems-Anderson 2018). All vehicles, even if not CV enabled, benefit from the data retrieved from the CVs to improve traffic information messages that may be received via roadside messaging signs or the wyoroad.info travel information portal. Furthermore, the Wyoming project includes a unique partnership with the atmospheric academic/research community and private weather enterprise to support CVs. Such partnerships in support of CVs could serve as a model for future AV development and deployment.

The AV community similarly has some work to do in order to be ready for weather challenges facing the technology. An increasing prevalence of private sector partnerships sparks promise in the future interactions between our respective communities. Currently, many organizations are partnering or exploring partnerships to address weather-related AV implementation challenges (e.g., Markets Insider 2020). Business to business partnerships between weather and transportation enterprises are a direct acknowledgment of the future weather needs for AVs; however, once again the direct involvement of the automotive manufacturers is lacking. The competitive and venture capital seeking nature of the AV community does not lend itself to the broad admission of technological limitations and needs for research collaboration. However, a broader coalition to address this convergent problem is crucial rather than case by case solutions with narrowly focused proprietary partnerships. The AV community will be unable to leverage the full capacity of the AMS community if open relationships are not developed.

Use cases and missing links

Several AV use cases exist to highlight the complex nature of weather needs and challenges. AVs will influence a broad spectrum of mobility including, but not limited to, commercial vehicles and freight, supply chain management and logistics, public transit and ride sharing, law enforcement and emergency services, and personal vehicles. Each of these mobility realms will have unique exposure to weather challenges. A commercial vehicle company

Fig. 3. Wyoming DOT connected vehicle pilot focused on weather impacts to public and freight traffic across Interstate 80 in Wyoming. Research partnerships with the National Center for Atmospheric Research have led to the development of a blow-over hazard risk decision support system.

with nationwide operations will need high-resolution road weather information across much larger spatial domains, longer time horizons, and assessments of how weather conditions may impact its operations from coast to coast. Municipality emergency services and public transit on the other hand will require finer spatial and temporal resolution specific to their locality. Personal travelers will need weather information specifically to match their planned travel whether for local commuting or longer trips. These mobility realms create a challenge for both communities to ensure the provision of accurate and appropriate multiscale and multimodal weather information specific to the end user's travel needs.

As AVs experience accelerating advances in technology, the engagements between the meteorological and transportation communities will be crucial to overcoming the barriers to complete adoption and implementation. In terms of situational awareness, onboard vehicle sensors may succumb to environmental conditions such as snow-covered roads, ice/road debris accumulation, and conflicting information (Kutilla et al. 2016). While some methods exist to compensate for loss of vehicle sensor information, such as digital base maps from private sector providers (L3Harris 2019), it remains unclear if these methods would provide sufficient spatial and situational awareness, especially in the context of non-fixed obstructions such as other vehicles and pedestrians.

Vehicle performance and maneuverability in adverse conditions presents a daunting task for AVs. In addition to ethical considerations for AVs (Bonnefon et al. 2016; Awad et al. 2018; Maxmen 2018), a common question is how will the vehicle respond as a human driver might presently. Conventional wisdom and defensive driving resources provide drivers today with many options to safeguard against loss of control during adverse weather such as increasing following distance, operating at slower speeds, firm braking, and steering in the direction you desire in the event of a skid [American Automobile Association (AAA); AAA 2019]. It remains to be seen if AVs will be able to sufficiently negotiate all of these challenges in all terrain and weather conditions, dependent on the particular level of automation. Further, there may be times in which travel is simply too dangerous. For example, it is unknown if AVs will understand the difference between a wet road that may be slick due to oils on the roadway, standing water that may create hydroplaning conditions during intense rainfall, and a completely impassable flooded roadway. Moreover, there may be no safe speed to traverse a steep, curved hill during an ice storm. Other considerations include AV operation during large, destructive hail events or high wind gusts. It is not clear how well AVs will obtain critical information beyond the range of their own individual sensing capabilities, even with connected vehicle technology. The algorithms, sensors, and artificial intelligence associated with AVs must account for tremendous amounts of uncertainty in such situations. The manufacturers must address these concerns with the assistance of broader engagement with the entire meteorological community.

While future challenges for successful AV implementation may seem daunting, their success yields many benefits beyond transportation network safety, efficiency, and reliability. The mobile, in situ data obtained from AVs may provide a host of microscale weather information on previously unattainable spatial and temporal scales. These data can further enhance numerical weather prediction and decision support systems in a mutually beneficial relationship (Anderson et al. 2015). For example, automated and connected snowplow fleets can more efficiently and strategically clear roads during significant winter storms (Fig. 4). Further, the research and development needs for successful AV implementation will promote cohorts of multidisciplinary research scholars, engineers, meteorologists, and decision-makers.

Summary remarks

While the fundamental question remains, whether or not the weather will dampen self-driving vehicles, the potential for AVs to revolutionize society is great. A future vision for AVs entails

their safe, reliable operation in all weather conditions across all levels of automation. To date, manufacturers have not fully embraced complete engagement with the meteorological community due, in part, to other considerations such as security, ethics, and getting the technology to perform correctly under normal conditions. Now, with AVs expanding their market share, addressing the “normal” variability of weather conditions is critical. The meteorological community and the entire weather enterprise stand ready to support the implementation and critical needs of AVs in the face of current and future weather and climate challenges. While the current outlook may seem bleak, albeit hopeful, open engagements between the AMS and AV communities will likely identify new avenues for future collaboration along with new challenges and opportunities.

CONNECTED VEHICLES & ROAD WEATHER: ILLUSTRATIVE CONCEPT

Fig. 4. Successful connected and automated vehicle (CAV) implementation may allow snowplow echelons to strategically and efficiently clear roads during significant snowstorms with bidirectional communications to other vehicles and transportation network users to identify both better routes to traverse with improved pavement conditions and those remaining degraded road pavement conditions segments.

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