Vehicle Automation and Weather: Challenges and Opportunities

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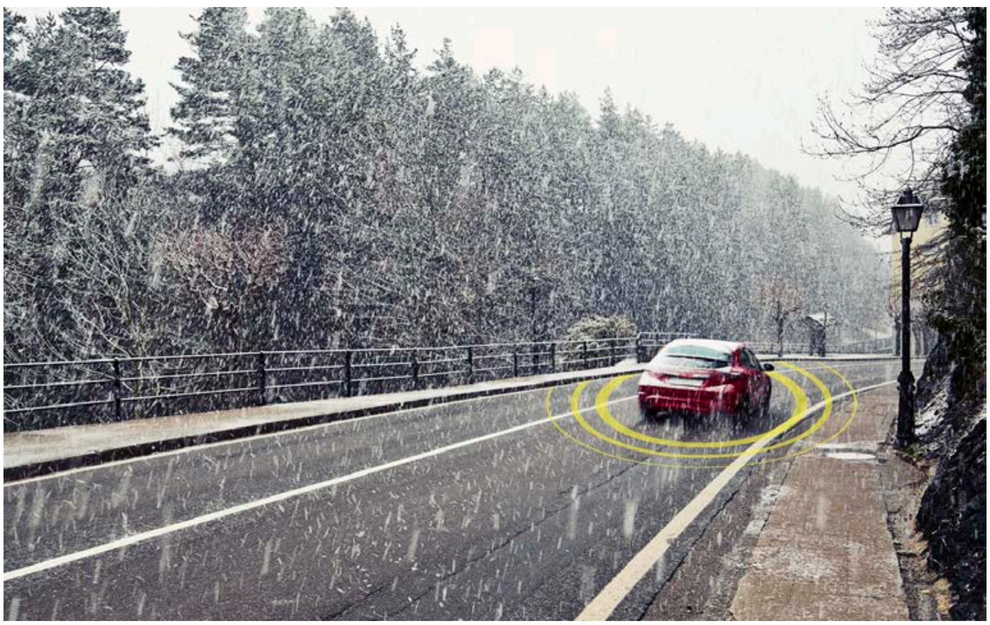

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16. Abstract

Adverse weather has major impacts on the safety and operations of all roads, from signalized arterials to Interstate highways. Weather affects driver behavior, vehicle performance, pavement friction, and roadway infrastructure, thereby increasing the risk of crashes. Most literature on weather effects have focused on collision risk, traffic volume variations, signal control, travel pattern, and traffic flow parameters. However, there is limited literature that characterizes vehicle performance under adverse weather conditions at different levels of automation. This paper discusses the relationship between weather and automated vehicle (AV) performance, including challenges caused by weather, data that can help alleviate some of these challenges, and new road weather data generated by AVs. Additionally, the U.S. Department of Transportation (USDOT) Road Weather Management Program (RWMP) has invested in several research efforts that support real-time road weather information. These efforts are very valuable and could play an important role in the development of advanced safety applications for automated vehicles.

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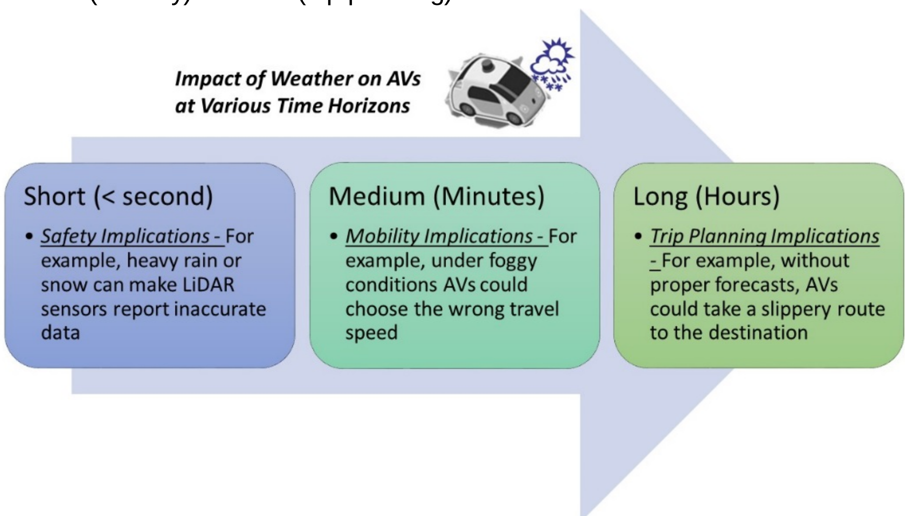
Abstract

Adverse weather has major impacts on the safety and operations of all roads, from signalized arterials to Interstate highways. Weather affects driver behavior, vehicle performance, pavement friction, and roadway infrastructure, thereby increasing the risk of crashes. Most literature on weather effects have focused on collision risk, traffic volume variations, signal control, travel pattern, and traffic flow parameters. However, there is limited literature that characterizes vehicle performance under adverse weather conditions at different levels of automation. This paper discusses the relationship between weather and automated vehicle (AV) performance, including challenges caused by weather, data that can help alleviate some of these challenges, and new road weather data generated by AVs. Additionally, the U.S. Department of Transportation (USDOT) Road Weather Management Program (RWMP) has invested in several research efforts that support real-time road weather information. These efforts are very valuable and could play an important role in the development of advanced safety applications for automated vehicles.

Introduction

There are technical and social acceptance obstacles that must be overcome before the full potential of automated vehicles (AVs) can be realized. Today, most AV applications or technologies are tested in clear weather conditions for safety reasons. AVs must be tested in adverse weather conditions in order to change social perception and thus social acceptance of this technology. Figure 1 shows how the performance of AVs is influenced by weather across the spectrum of time from milliseconds (safety) to minutes (mobility) to hours (trip planning).



Source: Booz Allen Hamilton, April 2016

Figure 1. Impacts of Automated Vehicles at Short, Medium, and Long Time Horizons.

The U.S. Department of Transportation crash statistics show that 93 percent of car accidents are a result of human error. Drivers make errors while driving due to a variety of reasons, including being drowsy, distracted, intoxicated, or simply failing to process information fast enough to make good driving decisions. On average, there are over 5.7 million vehicle crashes each year. Approximately 22 percent of these crashes – nearly 1.3 million - are weather-related. Weather-related crashes are defined as those crashes that occur in adverse weather (i.e., rain, sleet, snow, fog, severe crosswinds, or blowing snow/sand/debris) or on wet, snowy, or icy pavement. On average, nearly 6,000 people are killed and over 445,000 people are injured in weather-related crashes each year. [1] Thus, eliminating the human error factor by advancing automation is a logical progression to reduce the number of crashes and save lives. However, the system has to be reliable in all types of environmental conditions to achieve these benefits and to gain the public's confidence by the public that they are worth the investment.

[1] URL: http://www.ops.fhwa.dot.gov/weather/q1_roadimpact.htm , Accessed in April 2016

Some auto manufacturers have started to test autonomous features in snowy and rainy conditions but have not yet mastered such operations. Some auto industry and technology experts still suggest the first true self-driving cars will hit the market by 2020. Others say they will make up the majority of the vehicles on the road by 2035, replacing all others by 2050.[2] To accomplish driverless vehicle systems, the industry envisions a system of vehicle-to-vehicle communications, cameras, a variety of sensors (RADAR, LiDAR, RFID, etc.), and other devices integrated with advanced algorithms that can monitor the road in a variety of roadway, weather, and traffic conditions.

AVs will be fitted with a suite of sensors that provide important data for control algorithms that help the vehicle maneuver based on detected conditions. These sensors will generate a plethora of new data sets that are not otherwise currently available. For example, there are new in-vehicle technologies that can differentiate among precipitation types. This information can be very useful to the weather community and has the potential to make forecasts, warnings, and predictions more accurate.

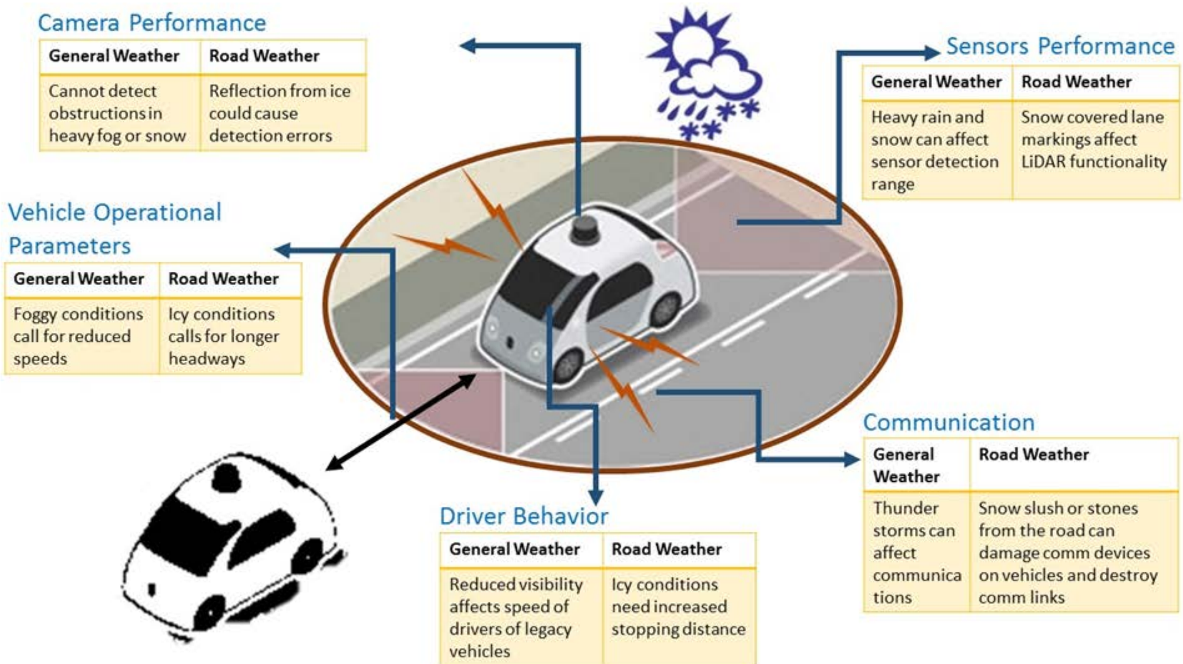
This paper explores the challenges posed to AVs by different weather conditions, data needs, and existing data sets pertaining to weather and road condition. It explores AVs as a new data source, and provides insights based on this discussion. The paper closes with a list of research needs and other factors that need to be considered in order for AVs to succeed in all environmental conditions.

[2] URL: http://www.southwestclimatechange.org/blog/19400, Accessed in April 2016

Challenges for Automated Vehicles in Adverse Weather

Recently, vehicle manufacturers have introduced several automated features that fall under the National Highway Traffic Safety Administration's Level 1 (function-specific automation) through Level 3 (limited self-driving automation) of automation. These features include adaptive cruise control, automatic braking and lane keeping, park assist, and traffic jam assist. These applications primarily rely on a family of sensors and camera systems. Adverse weather conditions such as fog, heavy rain, snow, and wind can severely limit the functionality of sensors and cameras. Although the applications appear to work well in dry, sunny weather, those are just the best-case scenarios. The real test for autonomous vehicle applications will be when the roads are wet or even icy and invisible to the sensors. There are a host of challenges when it comes to driving in bad weather that humans have learned to manage — but computers have not. Though some devices such as RADARS perform better than humans (e.g., detect an obstruction in foggy conditions), they may not be able to work independently to improve safety. Weather can be classified as general weather or road weather. General weather relates to measures, such as air temperature, precipitation type, fog, and dust, while road weather relates to pavement conditions, such as surface temperature, surface condition, and friction coefficient.

General weather and road weather can affect the performance of AVs in many ways. Figure 2 captures some of these impacts, which are further described below.



Source: Booz Allen Hamilton, April 2016

Figure 2. Weather Impacts on Automated Vehicles.

Sensors Performance

Unfavorable road weather conditions are a major barrier for sensors used in autonomous vehicle systems. Many of the sensing technologies currently used for prototypes and testing perform poorly during adverse weather conditions. For example, the LiDAR sensors, which emit short pulses of laser light, cooperate with cameras to sense nearby objects and allow the automated vehicle to create a real-time, high-definition 3D image of its surroundings. This works extremely well in clear weather but neither LiDAR nor other sensors are able to function accurately once the road is covered with snow. On the other hand, the forward RADAR is very good at detecting fast-moving large objects and can see through fog, rain, snow, and dust, but cannot operate independently to enhance safety applications. Falling snow could trigger the ultrasonic sensors in a vehicle to beep continuously issuing false alarms of obstructions when there is nothing around the vehicle. Reflectivity caused by wet and icy surfaces or glares from the sun can result in faulty readings and impact sensor accuracy as well.

Camera Performance

Camera systems are increasingly used to develop AV applications. Camera images are affected the most in fog, heavy rain, snow, and dusty conditions. Robust image processing algorithms help address some of these issues but reliability and accuracy remain a question. Sunny dry conditions could also cause problems of glare and compromise functionality when needed. However, these complex algorithms can help to detect dangerous weather conditions in real-time.

Vehicle Operational Parameters

Weather also affects several operational parameters of a vehicle. For example, when there is loss of friction and the roads are slippery, vehicles need to reduce speed and maintain a safe distance behind other vehicles so that there is enough stopping distance in an emergency situation. Driver behavior discussed earlier can also have similar effects on vehicle operational parameters in adverse weather conditions.

Driver Behavior

Even once AVs are deployed, driver behavior will still be a consideration. AVs will need to operate in a mixed environment (containing legacy cars and AVs). Therefore, AV applications should take other drivers, pedestrians, and external events (e.g., work zone, incidents, emergency response) into account for operational safety. For example driver state monitoring is critical to enable proper transition of control from the vehicle to the driver and vice-versa at different levels of automation. Similarly, it is important to understand driver behavior in different weather conditions to enable the development of effective AV control algorithms.

Communications

Weather affects the latency of communication systems and in some cases disrupts line of sight for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Maintaining low latency is critical for safety applications. Snow has little effect on radio-based communications, but thunderstorms or solar storms could cause serious concerns. Fog, heavy rain, snow, and hail can compromise line of sight for visible light communications (VLC), thus breaking the communication link.

Lack of Defined Standards

With respect to connected vehicles, RWMP application use cases have identified needs and gaps in existing technical standards. Consequently, several efforts are underway to update existing standards (such as J-2945x) to support the development of advanced road weather applications. However, characteristics or requirements pertaining to AVs are currently not part of this effort because they are not yet known. Though connected automation is seen as the next step forward, the road weather data needs for connected vehicles can be very different from the road weather data needs for AVs.

In addition, several other factors, such as deteriorating road surface conditions, heavy winds, and hail, require advanced and complex algorithms just to detect conditions, let alone control the vehicle in these adverse conditions. As a result, longer headways, speed reductions, varying driver reaction times to take control of a vehicle, etc., need to be taken into account in order for AVs to safely operate under adverse weather conditions.

Data Needs for Automated Vehicle Operation in Adverse Weather

In order to operate under all conditions, AVs will need accurate and timely weather and road condition information. For better understanding, the data sets have been grouped into three categories. Note that there is a difference between general atmospheric weather data and road weather data. These are explained in the descriptions below.

General Weather Data

This category includes data on current or forecasted general weather conditions that can help AVs with real-time control strategies (e.g., reduced speed) or route planning (e.g., alternate route or delayed travel) in advance of a trip. Current RWMP applications and data environments have demonstrated how this information can be provided with greater temporal and geographic resolution. Data may include air temperature, humidity, visibility, wind gusts, precipitation type, and intensity.

Road Weather Data

Data sets under this category include current or forecasted road condition information that can help AVs with real-time control strategies or to plan trip routes in advance based on forecasted pavement conditions. Current RWMP applications could provide this valuable information. Data sets include pavement temperature, pavement condition (icy/wet/dry), friction coefficient, snow accumulation, and ice build-up on the road/shoulders.

Crowd Sourced Data

Crowd sourced road weather data, usually obtained from the public provide valuable weather and road condition information in real time. Unlike the two data sets described above, this data is not a measured value but rather a subjective observation of road and weather conditions. For example, people may report that only a particular segment along a freeway is experiencing heavy rains or flooding when weather monitoring systems may not detect such conditions. These data sets not only help traffic management center (TMC) operations, but can also have a profound impact on AV application performance.

Other Data

There are other data sources that may be of importance to AV applications in adverse weather. For example, high definition three-dimensional (3D) maps, which include everything about a given stretch of road down to the signs and topography, can solve some problems in adverse weather. In a snowstorm, if a vehicle cannot see lane markings, the 3D maps can help the vehicle orient itself by detecting above ground lane markings. These detailed maps are created by driving a given stretch of road in clear weather conditions to capture images and details.

Existing Road Weather Data Sets

The RWMP has invested in several robust and comprehensive data management systems that are valuable and could be foundational in the research and development of AV applications for adverse weather conditions. The relevant data sets readily available from different data environments (e.g., Weather Data Environment) can be potential inputs to different AV applications. These inputs range from sensor data (e.g., air temperature, pavement temperature) to weather forecasts with temporal and geographic accuracy. A couple of existing RWMP data sources are described below.

Vehicle Data Translator (VDT)

This incorporates many connected vehicle-based data elements, including timestamp, latitude, longitude, air temperature, air pressure, speed, brakes, anti-lock braking system (ABS) status, traction control event, wiper status, dew point temperature, and surface temperature. It also ingests weather data from the National Weather Service to perform quality tests on all mobile observations. The output of the VDT are map-based, one-mile road segments with corresponding descriptors of road weather hazards.

Weather Data Environment (WxDE)

The Weather Data Environment (WxDE) is a research-based data system that acquires, validates, stores, and shares transportation-related weather data. The WxDE collects data in near real-time from both fixed environmental sensor stations (ESS) and mobile sources. It then quality checks the observations, and makes the data available either through a map interface or through queries and subscriptions. Furthermore, the WxDE integrates with the Research Data Exchange (RDE) so that transportation-related weather data can be easily accessed for researchers and application developers.

Automated Vehicles as New Source of Weather Data

Given that AVs require extensive sensing capabilities (e.g., RADAR, LiDAR), it makes sense that these sensors might also provide a new source of road weather observations. However, limited published research results are available in the areas of testing the sensing performance of AV prototypes, especially in adverse weather conditions. A few applications that were developed to detect adverse weather and road conditions are listed below.

- Researchers at the French Institute of Science and Technology for Transport have developed a unique methodology using backscattered veil and halo around light sources to detect and characterize the presence of night fog by assigning a visibility index in real time. The proposed methodology can deal with all lighting conditions and helps vehicles detect fog intensity in real-time.[3]
- General Motors has filed a patent for monitoring road weather conditions, specifically detecting wet road surfaces via a vision-based algorithm.[4]
- Jaguar's pothole alert system identifies the location and severity of potholes, broken drains, raised manholes, and similar hazards, and can warn upstream vehicles and maintenance managers.[5]

Based on the above observations, data from AVs can enrich several existing data sets with real-time updates. Table 1 summarizes potential benefits AV data can bring to existing databases and applications.

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[3] Gallen et al.: Nighttime Visibility Analysis and Estimation Method in the Presence of Dense Fog, IEEE Transactions on ITS, Vol. 16, No. 1, February 2015

[4] URL: http://www.freepatentsonline.com/9090264.html, Accessed in April 2016

[5] URL: http://www.digitaltrends.com/cars/jaguar-land-rover-tests-experimental-pothole-alert-system/, Accessed in April 2016

Table 1. Potential Benefits of Automated Vehicle Data

Data Type	Datasets Provided by AV Sensors
General Weather	Detect current weather conditions accurately with LiDAR/RADAR and Cameras (e.g., LiDAR can detect precipitation type, and light intensity, and cameras can detect fog intensity)
Pavement Condition	Accurately classify pavement condition (e.g., cameras can detect wet, dry surface conditions and RADAR can detect icy conditions; grip/friction, potholes, and flooding are other conditions that can be detected)
Maps	Provide real-time updates to existing high definition (HD) maps with hazards and obstacles caused by adverse weather (e.g., fallen tree on the road, flooding across specific segments of roadway)
Performance Measurement	Provide continuous HD data to help monitor road and traffic conditions during adverse weather conditions
Forecasts and Prediction Tools	Provide information that is not commonly available, such as flood prone road segments, freeze/thaw conditions, to further enhance forecasts and algorithms that output predictions based on historical data
Sensor Performance	Provide information on sensor data quality and performance issues during adverse weather so manufacturers can improve their products
Vehicle Diagnostics	Monitor and generate huge amounts of data that can provide valuable insights on how weather affects vehicle performance characteristics in real-time

Source: Booz Allen Hamilton, April 2016

Conclusions

The importance of AVs being able to operate under all types of weather and road conditions cannot be overstated. More complex solutions and systems will be required for AVs to operate under both fair and adverse weather conditions. Quality checked road weather data, along with accurate and timely forecasts for operational performance and safety, will also be necessary. It was noted that several of the data sets needed for AVs are available from various applications and data warehouses that the RWMP has already developed. However, these applications and data warehouses will need further development and refinement for operational scenarios. Additionally, AVs generate a range of data sets that can enhance existing road weather maintenance applications and improve the accuracy of forecast and condition prediction tools.

Considerations for the RWMP can be categorized as short-term, mid-term, and long-term milestones. Activities under these categories are described as follows, but are not limited to these milestones.

Short Term (0-3 Years):

- Conduct exploratory advanced technology research to better understand a number of factors (e.g., driver behavior, roadway characteristics, vehicle operational parameters, communications, and sensing) and their impacts on different levels of automation
- Include weather and AVs in simulation models for better planning
    - Adding weather aspects to current simulation models can help researchers understand and evaluate its impacts and effects under different use case scenarios
- Pursue technical standards for road weather applications and data
    - Establishing road weather standards would help advance the development of interoperable technology applications and accelerate deployments.

Medium Term (3-7 Years):

- Develop applications that are able to function under different pavement conditions and different levels of automation
    - A good understanding of the four factors mentioned earlier (e.g., driver, pavement, vehicle, and communications characteristics) will help develop robust applications for different levels of automation
- Refine established standards
    - Update existing standards and establish new ones as necessary based on stakeholder inputs, new technology advances, and pilot programs.

Long Term (7-10 Years):

- Integrate road weather nowcast/forecast models into vehicles for pre-trip and en-route planning
    - Move from research to implementation and deployment; integrate successfully tested applications and algorithms into vehicles
- Make AVs that are capable of operating in all low intensity weather conditions
    - Perform pilot tests and evaluate the new applications that are integrated into vehicle systems under low intensity weather conditions
- Develop appropriate fail-safe approaches in severe weather conditions.

APPENDIX A. List of Acronyms

Acronym	Definition
AV	Automated Vehicle
ESS	Environmental Sensor Stations
HD	High Definition
RDE	Research Data Exchange
RWMP	Road Weather Management Program
TMC	Traffic Management Center
USDOT	U.S. Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VDT	Vehicle Data Translator
VLC	Visible Light Communications
WxDE	Weather Data Environment

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