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Connected, autonomous cars: Passive pothole patrollers

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In November 2018, I was driving on the highway at night in upstate New York. The blowing snow and sleet made it difficult to see far ahead, but I noticed several cars pulled over on the side of the road with their hazard lights flashing. Assuming they had been in an accident, I pulled into the left lane when I suddenly struck an invisible obstacle, blowing my tires. After reaching safe location, I called 911 to relay what little information I could recall. I didn't know what I had hit or even where it was. That evening, half a dozen motorists struck the same hazard before authorities arrived on the scene.

This incident raises several questions. Was this unseen threat obvious to drivers earlier during the day? What if the other drivers had been able to warn me of the impending danger? How many similar hazards go undetected by maintenance crews, and how much damage do they cause?

Studies have shown that providing drivers warnings a few seconds before a potential collision could eliminate 60% of accidents that occur on motorways (R. R. Knipling et al., 1993). Modern vehicles incorporate hundreds of sensors and have increasing computational power. In these vehicles, advance-warning information is generated in real time by radar, lidar, and stereo-vision systems, allowing vehicles to warn drivers of lane departures, predict collisions, and even act on these observations by braking or steering. Vehicles of the future will be smart and connected. Cars today are being released with a host of cameras, sensors, and intelligent driving capabilities designed to improve occupant safety.

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Autonomous cars or those with advanced safety systems would continually monitor their environments, collect data, and search for any kind of hazard. Future cars will detect myriad road hazards, such as potholes, snow, slippery surfaces, and other obstructions. The sensing and connectivity capabilities of vehicles will grow exponentially. For these systems to work, they need to be reliable and fast; however, such detectors are expensive to build and increase the complexity of automobiles. Systems that rely on accurate detection are less likely to function in adverse conditions.

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Vehicular communication

Rather than relying on ultrafast detectors, why not communicate between vehicles? It is predicted that communications-based safety systems will be far more effective than the embedded systems built into vehicles (F. Ahmed-Zaid et al., 2011). The rollout of faster future connectivity and specialized communications protocols will allow for massive bandwidth, powering vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X)/infrastructure communication. The combination of these technologies forms a massive edge-computed, wireless sensor network that can be rendered for the public good.

The immediate relay of hazard location and risk to nearby vehicles could reduce the risk of accidents. More than 23% of yearly vehicle accidents are rear-end collisions (S. E. Lee et al., 2007). Much of the development of V2V communication is focused on providing additional information to drivers, warning them of unseen obstacles as a complement to onboard sensors. The biggest advantage of making vehicles or infrastructure able to communicate with drivers is that they could warn of an impending danger before sensors can perceive it (Fig. 1). Providing an early warning system of upcoming obstacles, such as potholes or deer in the road, could reduce this risk.

A network architecture designed for efficient communication routes information to appropriate destinations based on priority. Immediate hazard information is classified as high risk and safety related. It is critical that these data are transmitted to the affected vehicles quickly to prevent an accident. Lower-priority data, such as weather conditions, can be transmitted with a greater delay. As of 2019, there was no standard for V2V or V2X

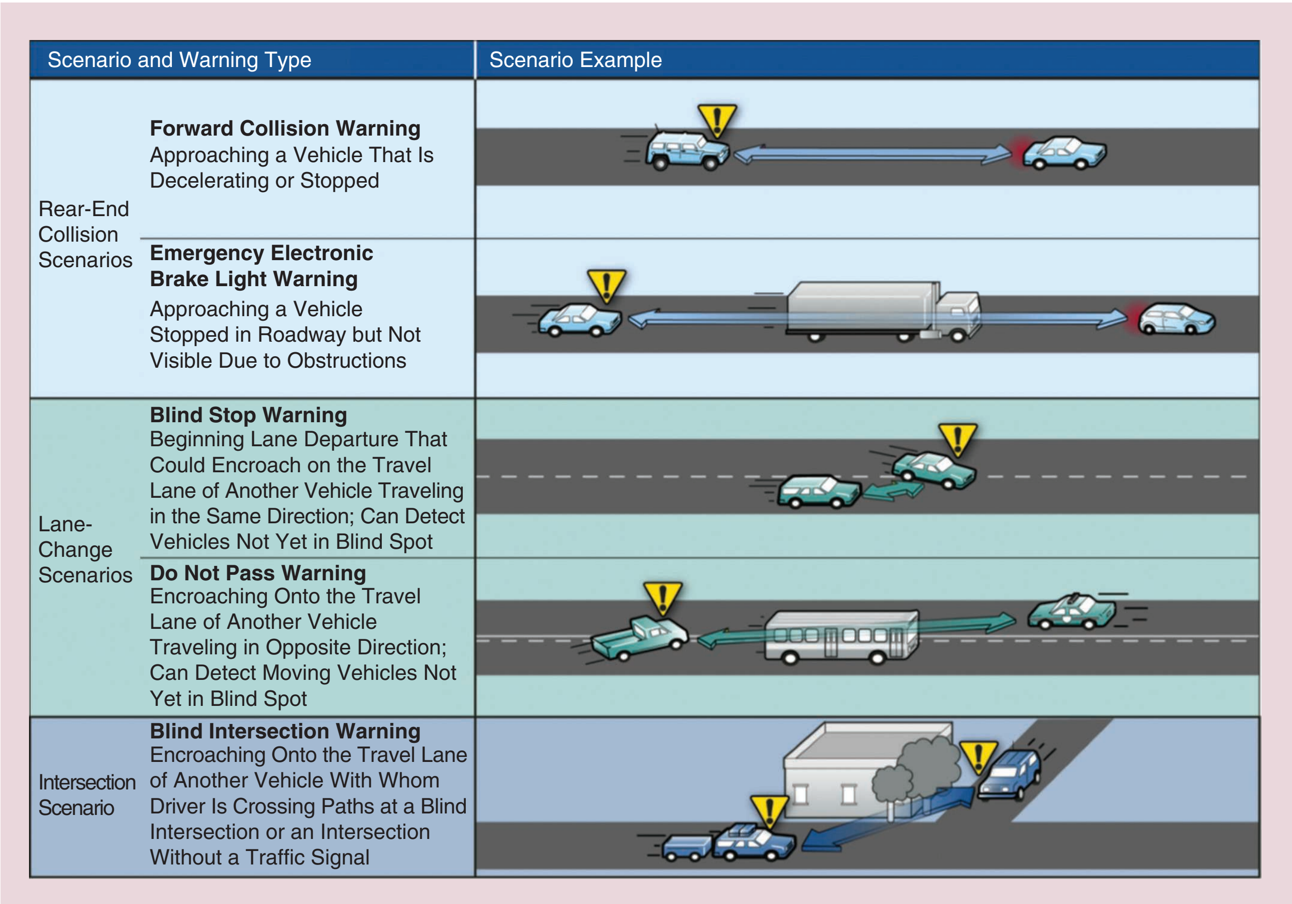

FIG1 The U.S. National Highway Traffic Safety Administration interaction scenarios.

Autonomous or smart cars can assist other smart, autonomous, and traditional cars by reporting hazards in real time.

communication, but there are several competing efforts in development.

The U.S. Federal Communications Commission assigned a 75-MHz bandwidth at 5.9 GHz for dedicated short-range communication (DSRC). This band is intended to be used for V2V and V2X communications. Direct communication with DSRC would be limited to 1 km. Longer-range communication with DSRC is facilitated through ad hoc networks or mesh networking and are being explored through LTE-V2X and 5G. In a vehicular ad hoc network (VANET), each vehicle acts as a node within the network. These nodes generate information and route communication with vehicles within range; they are self-organized and communicate without other infrastructure. Current cellular communications technologies provide reliable, secure, and wide communication coverage. It is predicted that IEEE 802.11p will have a lower cost compared to cellular technology.

Autonomous or smart cars can assist other smart, autonomous, and traditional cars by reporting hazards in real time. This reporting would occur through direct V2V communication for immediate action by nearby vehicles.

Uses for vehicular communication

In addition to reporting road hazards, vehicular communication has the potential to improve many other aspects of driving. Safety-related information could be given a greater priority through separate RF bands or with a safety-aware routing protocol. Connected vehicles might share information about braking or acceleration directly and in advance. Even if a vehicle's brake lights are obscured, a following vehicle could still be alerted to actions. With the integration of fast, reliable vehicular communications and adaptive cruise control, future vehicles would be able to drive more closely together; this would improve not only traffic and road congestion but also fuel or energy efficiency by allowing vehicles to all travel within the same slipstream.

FIG2 A pothole in the road.

Road-hazard detection: An urgent use case for V2V/V2X

According to the American Automobile Association, from 2011 to 2016, 16 million American vehicles were damaged by potholes, to the tune of US$3 billion per year (Fig. 2). Each incident costs an average of US$300 to repair, and those who strike a pothole are likely to see three more incidents in the next five years. Municipalities spend millions of dollars on the maintenance and repair of roadways each year. In 2005, Michigan had more than 7,500 pothole-related damage claims filed against it.

Insurance companies receive more than 500,000 pothole-related claims annually. Despite the capital investment and risk, damage from road hazards remains largely unmitigated. This is partially due to the difficulty of monitoring the ever-changing condition of roads and predicting repair costs. It is difficult to estimate the annual cost to repair roads.

Current prediction techniques rely on extrapolation from past trends in repair; citizen reporting; or expensive, specialized vehicles. An estimate of repair costs for the next year is found by extrapolation from the last 10 years of data. Methods that rely on public reporting, either through hotlines or websites, are ineffective due to underutilization and are expensive to maintain. Public reporting takes only specific hazards, such as a single, large pothole, into account and does not classify or quantify generalized conditions. Visual inspection is carried out infrequently by expensive, specialized vehicles with a host of sensors. After the data are collected, feature extraction and classification are usually completed manually by technicians, where the quality of the results depends highly on the bias and quality of these reviewers. These surveys are carried out once every one to four years and cover only highways.

The majority of our road networks, that is, the municipal roads, are surveyed completely manually, and this methodology is expensive and time consuming. Current techniques are inadequate to accurately assess the condition of our roads, relying on highly accurate, single-pass measurement; crowdsourcing; or past trends, and they tend to focus on highways or high-traffic roads. A robust, effective solution would survey all roads more frequently without the need for human input.

Localized weather conditions create temporary hazards that would be challenging to locate with current techniques. It is difficult to predict the effects of rain, freezing water, and wet surfaces on roads. According to a 2003 U.S. National Highway Traffic Safety Administration study, 22% of all accidents in the United States were weather related, resulting in 1.4 million vehicle crashes, 600,000 injuries, and 7,000 fatalities. A system capable of locating and recording localized weather-related hazards, such as flooding or snowdrifts, could help save lives.

Road hazards: Sensors and detection

Road hazards can be detected through various methods and with myriad available sensors, including inertial measurement units (IMUs), 3D reconstruction techniques, and computer vision. For detecting potholes, a common approach is to use microelectromechanical system (MEMS) IMUs, including an accelerometer, gyroscope, and/or magnetometer. The IMU techniques look at the shocks and vibration resulting from the car driving directly over the obstacle. Obstacles can also be detected with longer-range lidar and vision techniques. A 3D laser or lidar and stereo-vision algorithms generate a point cloud that may be used to create a 3D reconstruction of the road surface ahead, which can be analyzed for deformities. Potholes and other hazards can be identified from single-vision cameras, video, or 2D images (Fig. 3).

Accelerometers and other MEMS inertial sensors have been increasingly used in road surface monitoring due to their low cost and availability. As a vehicle passes a pothole or other road hazard, the amount of vibration rises; it also increases linearly with the velocity of the vehicle. If acceleration variance in the vertical (z) axis exceeds an adaptive threshold, the event is recorded. Simpler algorithms look at the absolute Z, differential, standard deviations, or presence of zero-gravity condition.

The Z threshold represents the impact of the vehicle on a pothole as an impulse. A significant peak in the Z signal is represented by a value far beyond the normal range. The peak could be identified by looking at the first-order differential, where sudden increases in the derivative are indicative of a shock. When entering and exiting a pothole, the wheel may experience temporary free fall. When all three axes are below a certain threshold, no acceleration is being applied to the vehicle. Power spectral density estimation can also be used to detect potholes in accelerometer data.

The 3D reconstruction methods could utilize the same lidar that is used for localization and mapping in autonomous cars or the stereo-vision algorithms to generate a 3D model of the road ahead. A lot of work in autonomous cars is based on using lidar to map the environment. These data generate a detailed 3D map of the environment, called a *point cloud*, that can be used to analyze for surface defects. Clustering algorithms, such as random sampling and acquisition, group the points into distinct surfaces. These algorithms group the points on the road surface together, separating the defect points, which can be analyzed to classify the type and nature of the hazard.

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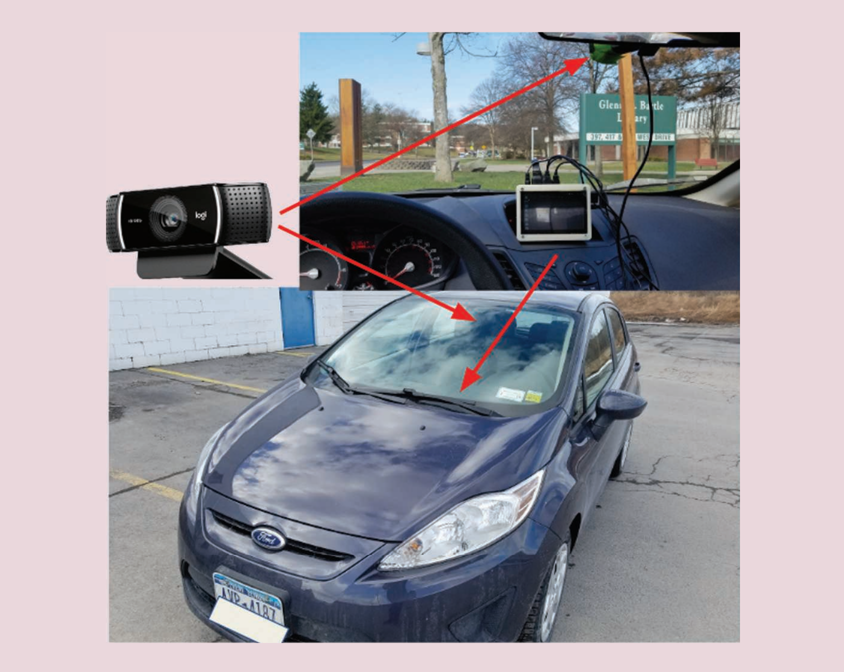

FIG3 A custom road-analysis system.

FIG4 Potholes can be detected with deep learning.

One of the main advantages to a road-hazard detection system based on a wireless sensor network is that the system does not rely on having a singular, perfect detector.

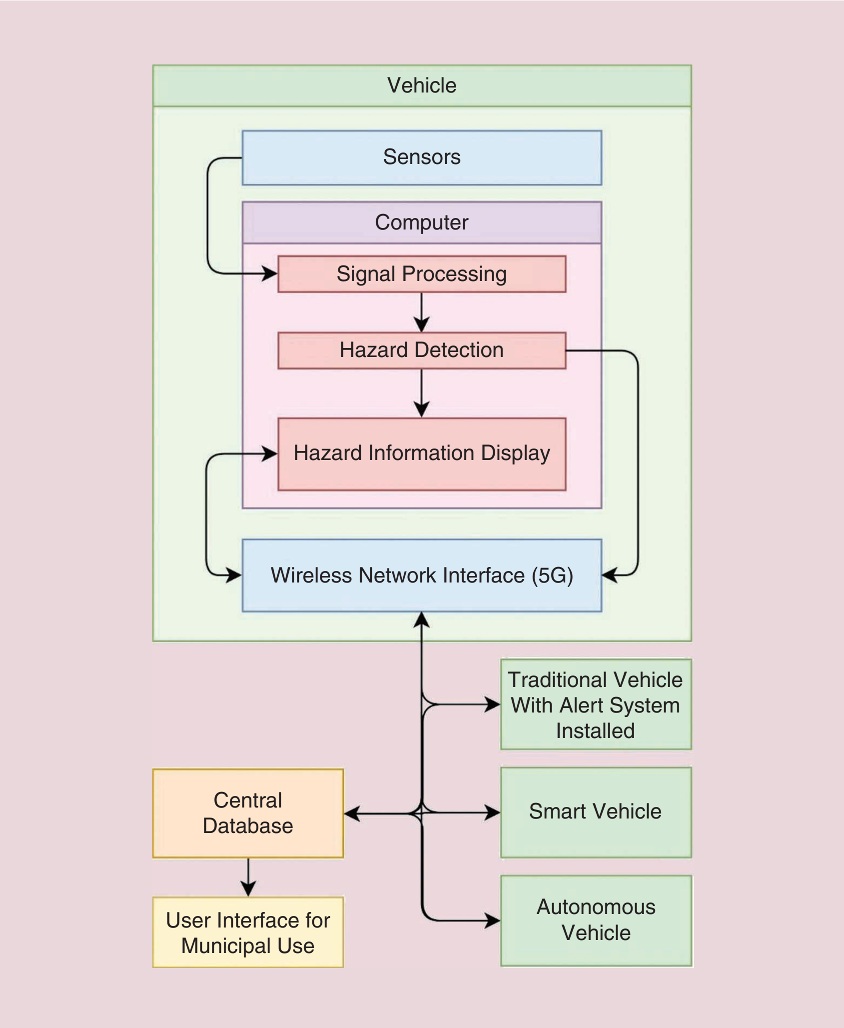

FIG5 A schematic chart for a hazard detection system.

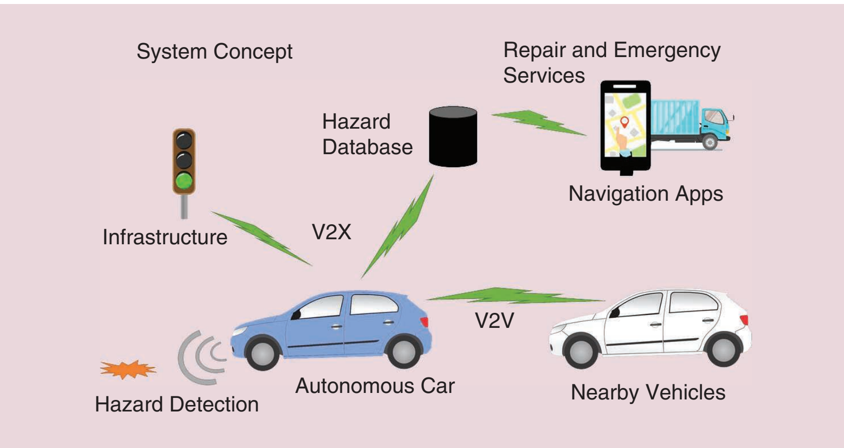

FIG6 An illustration of a hazard detection system.

accuracy and reliability. Potholes can be identified from their bowl shape and texture, and they have darker surrounding borders and a coarser, grainier inner texture compared to the surrounding road surface (Figs. 2 and 4). Filtering and histogram-shape thresholding can be used to extract these features and segment the image into defect and nondefect regions. The texture in the defect area is compared to that of the nearby nondefect area. Finding coarser, grainier texture in the segmented region is indicative of a pothole. Tracking a hazard in time with the video feed can further ensure detection.

More advanced techniques can detect and classify various road entities beyond simple recognition and localization. Using scale-invariant feature transform feature extraction and space-vector-modulation classification of a histogram of words, we see improved performance. These algorithms can be made simple enough to be implemented on microprocessors embedded within the camera.

Road hazards: Clustering and analysis

After a hazard is identified, its exact location must be determined and recorded. As it currently stands, data budgets are too low for the streaming of sensor data. This necessitates the use of edge computing, where the vehicle performs direct processing of the sensor data and relays only key geotagged and time-stamped information about conditions.

When a hazard is detected, only basic information (location, severity, time, and vehicle speed, among others) is relayed to the central database or distributed among vehicles. Fusing the inertia and speed of the vehicle, its GPS coordinates, and the relative position estimate from the hazard identifier together forms a reasonable estimate for its position. Each time a hazard is identified, its exact position is relayed to a centralized database as well as the nearby vehicles. Multiple passes over a singular hazard can be used to improve the probability that it is not a false detection. All local hazards can be clustered together in a mapping application.

One of the main advantages to a road-hazard detection system (Figs. 5 and 6) based on a wireless sensor network is that the system does not rely on having a singular, perfect detector. The results of multiple detectors from various separate vehicles passing over the same obstacle can be fused together. Each detector has its own probability of false alarm and probability of detection (PD). The weighted PD from each measurement can be combined to an overall probability that a hazard exists.

The quality of a road surface can be quantified by the number of hazards or surface roughness (Fig. 7). Roughness can be measured by the International Roughness Index or quantified into categories, which are typically defined as for OpenStreetMap's smoothness (excellent, good, intermediate, bad, very bad, horrible, very horrible, and impassible) or the ratings (excellent, good, qualified, and unqualified). According to the standard, normal cars can navigate excellent to bad or qualified roads. Municipalities could use the collected hazard database to plan repairs, dispatch service crews, and optimize snow removal services. Navigation software, such as Waze and Google Maps, would be able to access these data for improved route planning and to avoid treacherous roads.

When roads do not meet the standard of quality required to be passable, they need to be repaired. Detection information provides additional insight into the risk a hazard presents. Analyzing the time stamps of each detection shows the frequency with which an obstacle is encountered. A repair of high priority would be one that is both severe and subject to high traffic volumes. Every hazard can be ranked according to risk and assigned two costs: the cost to the public (that is, how many dollars in damage the hazard is likely to cause) can offset the cost to repair the defect. Presenting this analysis can produce further incentive for a local government to improve the condition of its roads. People would be able to directly see the return on investment of their tax dollars at work.

Challenges and future work

Security represents a significant challenge in the deployment of VANETs. Threats range from disrupting traffic to personal injury and death. Messages must be designed to both establish trust and also protect the anonymity of nodes. Government agencies are working with original equipment manufacturers (OEMs), such as Mercedes, Toyota, BMW, Fiat, Nissan, Ford, and others to implement prototype DSRC-equipped vehicles on roads.

The future of connected vehicles is still open. Standards organizations, such as the IEEE and Society of Automotive Engineers, and world governments will play a key role in the definition of how V2V systems will work. Every solution to this difficult problem requires coordination to become universal. The development of the technology behind vehicular communication will continue to require significant investment. Not only does communication need to be fast, but it also must also be secure, reliable, and accurate. For people to trust vehicular networks, they must feel comfortable with the concept.

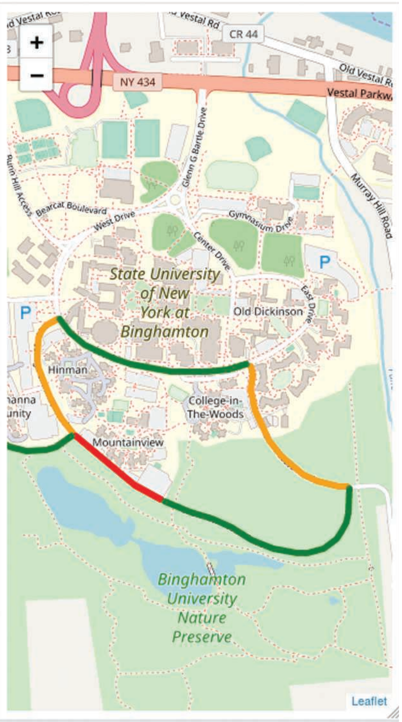

FIG7 A map showing road surface roughness.

Connected vehicle challenge

The SAE International WCX Connected Vehicle Challenge focuses on the development of innovative solutions that advance autonomous, connected vehicles for the public good. Hosted each year at the Cobo Center in Detroit, Michigan, the *Shark Tank*-style pitch competition featured seven finalist teams presenting their ideas for the future. Each team is competing for a US$10,000 prize, sponsored by Sirius XM and Solidworks, and the respect of the "celebrity" judges who represent major automotive OEMs, such as Ford and General Motors. The competition is open to both students and start-ups, with the submission deadline for project proposals in March.

Road hazard analytics

Road Hazard Analytics is a start-up focused on developing the sensors in a car to detect, track, and analyze the hazards faced on the road. Its goal is to leverage the technology of high-speed communications and autonomous vehicles to improve the lives of all commuters.

Modern vehicles come equipped with sensors, which scan the road ahead, and onboard computers that process the information. Data acquired from these sensors would be processed in real time using machine learning, which yields the location and type of each hazard detected. Any hazards that are identified are reported to an offsite central database and nearby vehicles also equipped with the system. When an upcoming hazard is reported on the current path of a vehicle, whether from nearby systems or the central database, an alert is presented to the vehicle's driver. Autonomous vehicles without drivers and route-planning

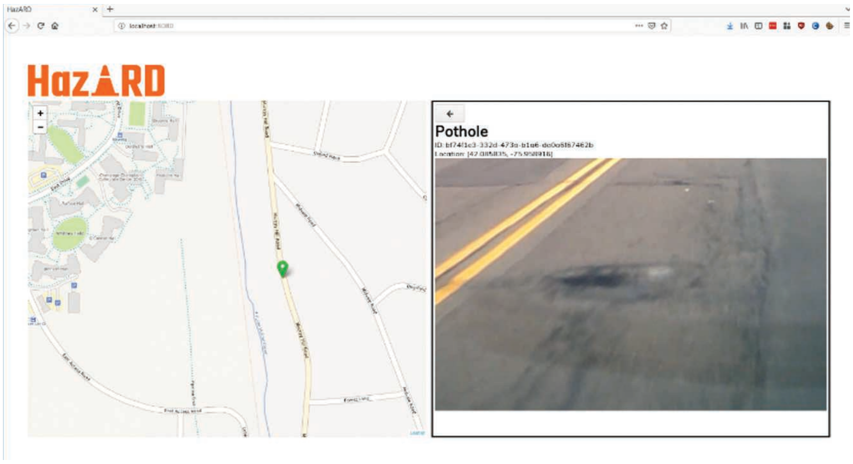

FIG8 An example of a municipal website.

software would use this information to determine if a lane shift or a path reroute is required and may alert any human occupants of impending conditions.

Hazards recorded in the central database are accessible through a web-based user interface. Municipal departments would be able to view a map or list of reported hazards, filtered by type, location, or frequency of detection (Fig. 8). Repeated detection by multiple vehicles reinforces the accuracy of the system and limits the number of false positives. This database allows road maintenance crews to rapidly determine the highest-priority repair locations or where to most effectively allocate snowplows. The evaluation of repairs could also be automated. For more information on Road Hazard Analytics, visit https://rha.ai.

Read more about it

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