

More Than Smart Pavements: Connected Infrastructure Paves the Way for Enhanced Winter Safety and Mobility on Highways

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Commentary

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Abstract

Currently, there is an urgent demand for more cost-effective, resource-efficient and reliable solutions to address safety and mobility challenges on highways enduring snowy winter weather. To address this pressing issue, this commentary proposes that the physical and digital infrastructures should be upgraded to take advantage of emerging technologies and facilitate the vehicle-infrastructure integration (VII), to better inform decision-makers at various levels. Driven by the paradigm shift towards more automation and more intelligent transportation, it is time to reimagine the vehicle-infrastructure ecosystem with the cold-climate issues in mind, and to enhance communications and coordination among various highway users and stakeholders. This commentary envisages the deployment of vehicle-to-everything (V2X) technologies to bring about transformative changes and substantial benefits in terms of enhanced winter safety and mobility on highways. At the center of the commentary is a conceptualized design of next-generation highways in cold climates, including the existing infrastructure entities that are appropriate for possible upgrade to connected infrastructure (CI) applications, to leverage the immensely expanded data availability fueled by better spatial and temporal coverage. The commentary also advances the idea that CI solutions can augment the sensing capabilities and confidence level of connected or autonomous vehicles. The application scenarios of VII system is then briefly explored, followed by some discussion of the paradigm shift towards V2X applications and a look to the future including some identified research needs in the arena of CI. This work aims to inspire dialogues and synergistic collaborations among various stakeholders of the VII revolution, because the specific challenges call for systematic, holistic, and multidisciplinary approaches accompanied by concerted efforts in the research, development, pilot testing, and deployment of CI technologies.

Introduction

Winter weather presents a host of profound challenges to the safety, productivity, reliability, and user experience of roadways in cold climates, through reduced visibility and pavement friction, compromised vehicle maneuverability, and decreased traffic speed and volume [Strong et al. 2010]. In the U.S. alone, traffic crashes on snowy, slushy, or icy pavements have been responsible for more than 1,300 human fatalities and more than 116,800 human injuries per year [FHWA 2011]. Fu and Kwon [2018] reviewed six case studies and found the reductions in traffic volume due to winter weather ranged widely, between 1.8% for light snowfall and 53% for heavy snowfall. Kwon et al. [2013] collected data for an urban freeway in Canada and their analysis suggested that the free-flow speed and capacity reductions were 17.0% and 44.2%, respectively, given a snow precipitation rate of 5 mm/hr and a Road Surface Index (RSI, a friction-like measure) of 0.2 (snow covered). Climate change can introduce such winter challenges to areas unfamiliar with snow and ice conditions or extreme cold-weather events.

Improving winter road maintenance (WRM) operations and traveler information services could result in fewer crashes, enhanced mobility, fewer emergency service disruptions, reduced travel costs, better fuel economy, and sustained economic productivity. To this end, it is desirable to use the most recent technological advances; current practices [Shi and Lu 2018] include many intelligent transportation

system (ITS) solutions such as smart snowplows equipped with automatic vehicle location (AVL), road weather information systems (RWIS), fixed automated spray technology (FAST), maintenance decision support system (MDSS), dynamic message signs (DMS), and traveler information systems. For traffic management, it is noteworthy that current ITS technologies (loop detectors, video/camera detectors, and radar sensors) are generally limited to obtaining traffic information at the macroscopic level [Wu 2018]. The advent of technologies in connected and autonomous vehicles (CAVs), Internet of Things (IoT), and advanced driver assistance (ADAS) systems, along with advances in information and communications technology (ICT), is envisaged to bring fundamental changes to the current practices.

The physical and digital infrastructures should be upgraded to take advantage of CVs/AVs and facilitate the cooperation between roadway infrastructure and CVs/AVs, i.e., vehicle-infrastructure integration (VII). In the near future, one expects to see mixed traffic flows of connected vehicles (CVs), autonomous vehicles (AVs), and conventional vehicles on highways. This presents new opportunities for better system performance and higher level of service, along with new infrastructure requirements. For instance, connected infrastructure (CI) solutions are desirable for bridging the communication gap between unconnected vehicles and CVs/AVs. CVs equipped with sensors could enhance mobile road weather data collection [Dey et al., 2015] and supplement or compliment current roadway sensing entities, raising the effectiveness of the system operations to react to changing conditions. The 360° awareness by vehicle operators and increased system reliability will help reduce the risk of vehicle crashes and enhance the efficiency of system operations. The Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) developed by the U.S. Federal Highway Administration (FHWA) has defined how CVs will contribute to various service packages including those for weather, vehicle safety, sustainable travel, traffic management, and traveler information [Iteris, 2020]. Earlier work also envisioned that CV technologies would enable traffic managers to deliver real-time, localized road weather advisories and forecasts directly to the vehicle onboard unit as a visual display to drivers [FHWA, 2014]. Moreover, collected real-time raw data can be shared with commercial application developers to build value-added services [Chapman and Drobot 2012]. AVs tend to be CVs at the same time and can offer a multitude of benefits including alleviated congestion, reduced energy use and emissions, and improved traffic safety [Shladover 2013, Sobanjo 2019].

Recent years have seen substantial progress in the development and pilot testing of technologies that enable CVs to transmit data to and receive data from other CVs (vehicle-to-vehicle, V2V), to and from infrastructure (vehicle-to-infrastructure, V2I), and to and from bicyclists or pedestrians. These can be collectively termed as vehicle-to-everything (V2X) communication, for which use cases, requirements, and design considerations of roadways have been discussed by Boban et al. [2018].

In the context of upcoming VII revolution and increased road user expectations, this commentary aims to inspire dialogues and synergistic collaborations among various stakeholders and across various disciplines. The commentary is organized in five main sections. Following this introduction is a discussion of conceptual design of next-generation highways in cold climates, including the existing infrastructure entities that are appropriate for possible upgrade to CI applications. Subsequently, the

application scenarios of VII system are briefly discussed, with a focus on coordinated truck platooning, safety applications, mobility applications, and road weather applications. The final sections provide concluding remarks regarding the paradigm shift towards V2X applications and a look to the future.

Fig. 1 presents a conceptual design of next-generation highways in cold climates, where a number of CI entities are envisioned. These, along with V2X and ICT capabilities, are expected to greatly enhance the spatial and temporal resolutions of road weather data and thus better inform stakeholders such as highway operators, emergency responders, truck drivers and other highway users. They can also augment the sensing capabilities and confidence level of CVs/AVs, reduce the cost and uncertainties of sensing, enrich the sources of information for both CVs/AVs and unconnected vehicles, and improve the response time.

The following sections will further discuss some entities shown in Fig. 1, including:

1. Connected Environmental Sensing Stations (ESS);
2. Connected FAST system;
3. ICT capabilities, including but are not limited to: a) roadside units, b) mobile connectivity, and global positioning system (GPS);
4. Energy-harvesting, connected roadways and roadside infrastructure assets (RIAs); and
5. Self-sensing or anti-icing pavement.

Note that the 4th and 5th components are secondary to the implementation of VII ecosystem but would greatly enhance the viability and value of VII. Other CI entities will not be discussed in detail, and those may include: weather-responsive traffic signals, smart work zone equipment, and non-contact static charging for vehicles. This work does not cover any discussion of AV-enabling infrastructure components, such as smart signage for automatic driving, standardized pavement markings for machine vision, and magnetic nails and reflective striping for lane-keeping.

Connected ESS

RWIS-ESS could be further enhanced so as to serve as integral part of the CI solution and of the larger vehicle-infrastructure ecosystem. Currently, this technology is mainly deployed at fixed locations to better inform WRM operations and travelers, and the deployment has been hindered by high cost and maintenance needs. RWIS refers to “networks of ESS that observe the near-surface atmosphere and pavement surface and subsurface” [Albrecht et al. 2018]. Each ESS consist of various sensors that provide site-specific, real-time data on the meteorological conditions, road surface condition (RSC), and subsurface temperature, which altogether enables pro-active WRM practices such as anti-icing, improves the roadway level of service and resource allocation, and enhances traveler information, traffic management and emergency response [Strong and Fay 2007, Kwon et al. 2017]. Note that the mobile data collection by CVs/AVs will likely bolster the accuracy of road weather forecasting models, which in

turn induces advances in the RWIS-ESS technology. This technology is going portable as well [Tessier, 2016], and its limitations will likely be overcome by design improvements and cost reductions.

Connected FAST system

FAST system is a system of fixed assets designed to spray anti-icing liquid on targeted ice-prone or safety-critical areas once the sensors (and associated algorithm) detect the likely risk of ice formation. Many roadway agencies have employed the FAST technology to prevent or pro-actively mitigate black ice or bonding of compacted snow and ice to pavement (or bridge deck). Conceptually, the design of FAST system could be further enhanced to improve its connectedness and thus contribute to the vehicle-infrastructure ecosystem. Ye et al. [2013] surveyed the state of the art of FAST systems and confirmed their potential in delivering substantial benefits, such as less need for mobile operations and WRM materials and reduced crash frequency and traffic delay. This technology “works best for frost and light snow events”, but its application has been hindered by challenges in sensor malfunctioning, system maintenance, and training. A study by Veneziano et al. [2015] examined the safety effects of FAST systems operated by the Colorado Department of Transportation and recommended the deployment of such system at “high-traffic, high-crash severity locations”. For instance, FAST systems were able to contribute to “an annual reduction of 16% to 70% on urban Interstates, 31% to 57% on rural Interstates, and 19% to 40% on interchange ramps between Interstates”, when sited and operated properly.

In the context of VII revolution, no single communication technology “(in the near future) can support such a variety of expected V2X applications for a large number of vehicles”, at least not efficiently [Abboud et al. 2016]. Currently, dedicated short-range communications (DSRC) and cellular networks are the two main technologies for V2X communications. Abboud et al. [2016] reviewed various DSRC-cellular hybrid architectures and discussed the interworking challenges between the two technologies, with DSRC transceiver embedded in RSUs interacting with in-vehicle onboard units (OBUs) as well as the backhaul network (via cellular or wired Internet connections). Dey et al. [2016] developed a method to optimize available communication options for V2V and V2I applications in a heterogeneous wireless network consisting of DSRC and “other wireless technologies (e.g., Wi-Fi, LTE, and WiMAX)”. Nonetheless, Jenkins et al. [2017] concluded that “DSRC for wireless access in vehicular environments (WAVE) (protocol) is (currently) the only way to provide V2X communications with high reliability and low latency” and thus suitable for dissemination of basic safety messages.

Now is the dawn of the 5G era, which stands for the 5th generation mobile network and features communication capabilities better meeting the needs of IoT and V2X applications, particularly safety-critical use cases [Boban et al. 2016]), i.e., higher data rates, ultralow latency, ultra-reliability, and increased availability. Boban et al. [2016] proposed an architecture of the 5G V2X network, embodied in a heterogeneous multi-radio V2X network designed to leverage the strengths of “cellular systems in centimeter (cmWave) and millimeter (mmWave) frequency bands, vehicular visible light communication (VVLC)” and DSRC/WAVE.

The computing infrastructure, either distributed or centralized, also plays a crucial role in the TCPS to enable smart and seamless mobility, and should be planned, designed, deployed, operated and maintained properly [Khan et al. 2019]. To attain outstanding performance and reliability of V2X applications, this Commentary sees that innovations are needed in the field of information technology in terms of system design, hardware and software. Naturally, one needs to tap into recent advances in edge computing, big data analytics, machine learning, artificial intelligence, and so on. For instance, Raza et al. [2018] described an advanced ITS based on ultrahigh speed, ultralow latency 5G scenario, where multiple networking technologies were integrated to provide ubiquitous network connectivity and efficient computing that supports V2X communications. Among them, edge computing (a.k.a., fog computing) refers to “the enabling technologies allowing computation to be performance at the edge of the network, on downstream data on behalf of cloud services and upstream data on behalf of IoT services” [Shi et al. 2016], and it brings many advantages in “addressing the concerns of response time requirement, battery life constraint, bandwidth cost savings, and data safety and privacy”.

Arguably, there are a number of roadside or CV solutions other than embedded pavement sensors that can augment the FAST’s detection capability and improve its reliability by providing additional information on the RSC. Promising technologies include non-invasive pavement friction sensors [Ewan et al. 2013], vehicle-mounted sensors for thermal mapping [Todeschini et al. 2016, Hu et al. 2019], slippery surface detection [Padarthy and Heyns, 2019], or RSC monitoring [Chen et al. 2011, Pu et al. 2019], and the combined use of mobile camera and smart phone [Linton and Fu 2016] or mobile RWIS technologies [Ye et al. 2012] for RSC monitoring. Most of them could be readily integrated with the AVL technology [Santiago-Chaparro et al. 2012] to unlock their potential in enabling more proactive, efficient and resilient WRM operations.

ICT capabilities

This commentary agrees that as part of the transportation cyber-physical system (TCPS), the physical infrastructure of roadways should be “upgraded with digital (ICT) infrastructure that evolves with increasing CV penetration levels (so as to) create an environment suitable for fostering beneficial V2I innovations” [Khan et al. 2019]. This is critical for enabling the timely and reliable sensing, processing and communication of the unprecedented amount of data available in the VII environment. Khan et al. [2019] summarized the typical roadway digital infrastructure components (as shown in Fig. 2), including roadside units (RSUs), traffic signals, loop detectors, traffic cameras, and DMS communicating with both CVs/AVs and the backend infrastructure (servers) in a real-time or near-real-time fashion.

Energy-harvesting, connected roadways and RIAs

Connected roadways need reliable supply of energy. The massive number of roadway mileages and vast amount of lands in the right-of-way present a great opportunity to capture and utilize the energy dissipated from the ambient roadway system, such as mechanical energy from vehicle or wind loadings and thermal energy from the sun or earth. Such energy harvesting is particularly beneficial for roadways in remote, off-grid areas where the lifeline of CI applications is endangered by the lack of access to power.

In the U.S. alone, there are 2.6 million miles of paved roads and highways, of which approximately 93 percent has an asphalt surface [Mohamed Jaafar 2019] and 3,000 (linear) miles are equipped with noise barrier [Poe et al. 2017]. The “(unpaved) land cover in close proximity to the National Highway System” in the U.S. has been estimated to be “roughly 68 percent, or 3.4 acres” [Earsom et al. 2010].

A suite of on-road energy-harvesting technologies are available, as illustrated in Fig. 3 [Wang et al. 2018]. These technologies entail the use of piezoelectric materials, micro wind turbines, photovoltaic panels or solar cell roads, geothermal heat pumps or pipe-pavement thermoelectric generator (PP-TEG) system. They could be potentially incorporated into either the connected roadways such as pavements and traffic signals, or RIAs such as noise barriers and structural snow fences, to meet the energy needs of a multitude of sensing and communication needs. They also feature a wide variety of cost, energy output and efficiency, service life, dimensions, maintenance requirements, recyclability, and other characteristics. Gholikhani et al. (2020) concluded that “thermoelectric and piezoelectric technologies are the most readily available methods” and Wang et al. (2018) discussed that technologies other than piezoelectric energy harvesters (PEHs) have their own strengths and limitations. For instance, photovoltaic systems can produce high energy output but the use of solar panels in roadways may complicate vehicle operations or pose a risk to traffic safety, and more research is needed to address such concerns. One promising niche application is solar-powered roadway lighting by [light emitting diode](#) (LED) (Yoomak et al. 2018). Geothermal heat pumps are considered a mature technology, which is “geologically and geographically limited” and most appropriate for safety-critical areas, and they have shown a desirable benefit/cost ratio for bridge deck de-icing (Habibzadeh-Bigdarvish et al. 2019). While PP-TEG produces a low energy output at high cost and more research is needed to improve the system efficiency (Zhu et al. 2019), a PP-TEG system can be potentially more cost-effective than a piezoelectric system in harvesting renewable energy from pavements (Guo and Lu 2017).

The last four years have seen increased interest and promising progress in demonstrating the use of piezoelectric materials to harvest deformation energy from asphalt pavement. Yet, the amount of energy harvested is limited but suitable for applications such as “powering wireless sensors embedded into pavement structure” [Roshani et al. 2017] and other microelectronics, “heating road surface on bridge deck for anti-icing, lighting, or powering traffic devices” [Wang et al. 2018]. A few representative advances in the development of piezoelectric energy harvester (PEH) technology is summarized in Table 1.

Table 1. Recent advances in PEH technology for roadways

<i>Configuration</i>	<i>Optimal energy performance</i>	<i>Other performance considerations</i>	<i>Reference</i>
A stacked configuration of transducers	Not reported	Able to support loadings up to 150 kN and remained effective after 100,000 cyclic loadings	Yang et al. [2017]
Stacked units including U-shaped interlayer copper foil electrode structure	Output power: 22.8 mW at a resistive load of 20 kΩ, under 0.7 MPa (compression loading) and 10 Hz (vibration frequency); output voltage: 28.0 V	Stable performance after 50,000 simulated cyclic loading, with attenuations of: open-circuit voltage by 4.4 V, output power by 3.3 mW	Wang et al. [2019]
Bridge transducer with layered poling and electrode design	Output power: 2.1 mW at a resistive load of 400 kW, under 0.07MPa, 5 Hz; output voltage: 556 V	Balanced the desire for improved energy output and the need for less risk of stress concentration	Jasim et al. [2017]
Several PEH prototypes to be embedded into asphalt pavement	Output power: > 25 mW under 15 MPa (for each piezoelectric element) and 10 Hz; output voltage (nearly 20 V) and output current (> 100 μA) at a load of 3 kN	Higher frequency “represents higher traffic speed and greater traffic volume” (e.g., on Interstate highways), and leads to better output power.	Roshani et al. [2017]
One layer of “piezoelectric elements with a higher piezoelectric stress constant” and two layers of “more flexible conductive asphalt mixtures”	Output power: ranging from 1.2 mW to 300 mW at 30 Hz	The cost of electricity produced by this PEH can be as low as “\$19.15/kWh at a high-volume roadway within a 15-year service life”.	Guo and Lu [2017]
A 100-m piezoelectric pavement with packaged multi-layer transducer	Output power: up to 231 mW (0.58 J), under 0.7 MPa	Under the daily traffic volume of 15100 vehicles, this 100-m pavement can produce up to 1.93 MJ (i.e., the energy needs of 35 mobile phones). The additional construction cost: approximately \$57/m.	Cao et al. [2020]

In addition to smart pavements, there are a number of conceptual scenarios that energy-harvesting technologies may be incorporated into the roadway infrastructure. For instance, portable micro wind turbines could be mounted on structural snow fences, traffic signals, and so on. Being a cost-effective technology to prevent blowing and drifting snow, snow fences can improve road safety and provide additional benefits, if designed and sited properly [Du et al. 2017]. Nabavi and Zhang [2016] reported

three groups of portable wind energy harvesters, i.e., piezoelectric-, electromagnetic-, and electrostatic-based generators, with different wind-flow-trapping mechanisms and varying dimensions and energy conversion efficiencies. Photovoltaic panels can be strategically installed either in the right-of-way providing sufficient space for such a “distributed solar power plant” [Asanov et al. 2019], or integrated with noise barriers to produce a considerable amount of renewable energy [Poe et al. 2017]. Qiao et al. [2011] proposed the concept of a “smart microgrid that optimally utilizes the public right-of-way and roadway infrastructure to provide cost-effective, highly efficient, and reliable wind/solar electric power production, distribution, storage, and utilization”. The design entails a “grid-connected wind/solar hybrid generation system installed on the pole of a roadway/traffic signal light”. Considering the great temperature difference between the air and the relatively warm soil beneath pavement, another potential technology to explore is thermoelectric generators. With the thermal gradient in the opposite direction, this concept was demonstrated in south Texas [Datta et al. 2017] where a TEG prototype produced “an average of 10 mW of electric power continuously over a period of 8 h”.

Self-sensing or anti-icing pavement

Self-sensing pavements can serve as an integral part of connected roadway infrastructure or VII system, and the related research is still in the burgeoning stage and the cost-effectiveness of this technology over the long term remains unknown. Han et al. [2013] reported the traffic detection performance of a self-sensing pavement being tested at the Minnesota Road Research Facility, USA, both in winter and in summer. This smart pavement was enabled by the admixed carbon nanotubes in concrete, and was able to “accurately detect the passing of different vehicles under different vehicular speeds and test environments”. Relative to conventional strain gauges, this self-sensing concrete exhibited advantages in its ease of installation and maintenance, compatibility with pavement structures, and durability. Liu et al. [2014] reported an exploratory study that suggests the potential use of conductive asphalt materials for self-sensing applications, because the different stages of damage evolution corresponded to certain change patterns in their electrical resistivity. Xiang et al. [2020] reported the use of piezoelectric sensors to detect moving traffic loads on pavement, i.e., for the weigh-in-motion application.

Anti-icing pavements are often not designed for CI applications, but they can contribute to the mobility of surface transportation system during snowy weather. A variety of technologies have been explored to enable anti-icing pavements, ranging from “anti-freezing pavements that rely on physical action, to high-friction *in situ* anti-icing polymer overlays, to asphalt pavements containing anti-icing additives, to heated pavements using energy transfer systems” [Shi et al. 2018]. All of them aim to “prevent or reduce the bond of ice or compacted snow to pavement or to prevent or treat winter precipitation”. Pan et al. [2015] and Zhang et al. [2020] presented a comprehensive review on the use of conductive and salt-releasing asphalt mixtures as anti-icing pavements, respectively. Saleh et al. (2020) discussed the design, construction and evaluation of hydronic asphalt pavement (HAP), which is another energy-harvesting technology explored for anti-icing (and deicing) applications. Johnsson (2017) found that HAP could be engineered as part of a system to harvest sufficient geothermal energy for areas with mild winters and greatly “reduce the annual number of hours with risk for ice formation”. Note that none of these

technologies have been widely adopted by transportation agencies, and this is mainly due to concerns over their long-term performance and cost. Nonetheless, this Commentary proposes that there is great potential in overcoming such technological barrier in the near future.

Application Scenarios Of Vii System

This section identifies some possible application scenarios of VII system, which are grouped into safety, mobility, road weather, agency data, and other categories, as detailed in Table 2. One can expect CI-enabled improvements to be materialized in these applications, given the notable advances in spatial and temporal coverage offered by CI technologies. The key to success is the timely and reliable sensing, processing and communication of the big data collected by the VII system. Table 2 is not intended to be comprehensive, as innovations may lead to new possibilities and new application scenarios.

It is noteworthy that the enhanced spatial and temporal resolutions of road weather data can better inform a multitude of stakeholders and produce benefits across the spectrum of many applications. Both road weather and agency data applications are intertwined with highway safety and mobility objectives, because they aim to “provide a safe and efficient transportation system to move people and goods” [Sobanjo 2019]. The USDOT V2I research program has developed a computing platform known as V2I hub [Chang 2017], which “interfaces with a variety of ITS equipment such as RSU, traffic signal controllers, and DMS” and the GPS and transportation management center (TMC). For instance, an RSU can broadcast intersection geometry data (a.k.a., MAP message), signal phase and timing (SPaT) message, GPS correction data, and curve speed warning to incoming vehicles, or receive them from nearby RSUs [Change 2017, NOCoE 2020].

Table 2. Some identified application scenarios of VII system

<i>Application Type</i>	<i>Application Scenario</i>	<i>Reference</i>
Safety	Cooperative-ITS platform: advance warning of hazardous road situations (to vehicle drivers)	Padarthy and Heyns [2019]
	V2X applications for roadway safety and vehicle safety	Abboud et al. [2016]; FHWA [2020]
	Intersection collision warning, emergency vehicle pre-emption, work zone alerts, curve speed warning, railroad crossing violation warning	Barbaresso and Johnson [2014]
	In-vehicle signage, oversize vehicle warning, red-light or stop-sign violation warning, reduced speed zone warning/lane closure, restricted lane warning, spot weather impact warning	Iteris [2019]
	Cooperative collision avoidance	Chowdhury et al. [2018]; Wang and Li [2019]
	Blind spot warning and lane change warning	Theriot et al. [2017]; Howe et al. [2016]
	ADAS functionalities	Liu et al. [2017]
	Pedestrian detection and warning	He and Zeng [2017]
	Deer crossing road detection: with multiple roadside LiDAR (Light Detection and Ranging) sensors deployed to enable real-time, micro-level and high-resolution sensing of road users	Wu [2018]
	Mobility	Coordinated truck platooning
Traffic management and sustainable travel		Li et al. [2020]; Gopalakrishna, et al. [2016]; Iteris [2020]
Advanced traveler information system, corridor management, transit vehicle priority, and multimodal intelligent traffic signal system		Barbaresso and Johnson [2014]
V2X applications for vehicle traffic optimization		Abboud et al. [2016]
Incident detection and response; traffic queue or bottleneck detection; traffic network flow optimization		Khazraeian [2017]; Chowdhury et al. [2018]
Emergency vehicle priority		Head [2016]
Adaptive signal control		Yao et al. [2020]

	Cooperative adaptive cruise control	Huang et al. [2020]
	Dynamic routing support	Genders and Razavi [2016]
	Smart DMS, routing support and data-driven apps for freight carriers, transit vehicles and emergency responders	Iteris [2019]; Akin et al. [2018]
Road weather	V2X applications for motorist advisories and warnings, information for maintenance and fleet management systems, and MDSS	Barbaresso and Johnson [2014]; Young et al. [2019]; FHWA [2020]
Agency Data	V2I applications for probe-based traffic monitoring, probe-based pavement condition monitoring, and performance measures	Barbaresso and Johnson [2014]; FHWA [2014]; Li et al. [2019]
Other	V2X applications for passenger infotainment (via in-vehicle Internet access) and car manufacturer services (e.g., point-of-interest notification and remote vehicle diagnostics).	Abboud et al. [2016]
	Value-added services by commercial application developers	Chapman and Drobot [2012]

The USDOT has estimated that combined V2V and V2I systems may potentially address about 81% of all-vehicle target crashes, 83% of all light-vehicle target crashes, and 72% of all heavy-truck target crashes [Najafi et al. 2016]. Such safety benefits of CV are likely to be more significant during adverse weather conditions, by enhancing all levels of decision-making by stakeholders. For example, the enriched road weather condition information can be communicated to the general public in a timely fashion, such that they can slow down, choose a different route, or stay home in light of inclement weather.

In addition to safety benefits, the deployment of V2X technologies and advances in VII are likely to produce mobility and resilience benefits on winter highways, by better informing all the stakeholders and enabling location-specific and timelier detection of and response to disruptions. By definition, resilience is “the ability of a system to resume normal function at a performance level equal that which existed before a disruptive event”, and can be characterized by metrics such as robustness, adaptability, agility, redundancy, response time, recovery time, level of recovery, and performance loss [Muller 2012]. The transmission of microlevel road weather data by vehicles through V2X communication has been demonstrated in the European WiSafeCar project [Sukuvaara and Nurmi, 2012], which is anticipated to benefit the efficiency of road weather management [Ma et al., 2012].

One major mobility application scenario is coordinated truck platooning. Connected and autonomous trucks (CATs) are increasingly introduced into the market, which enables the grouping of densely-spaced trucks to travel together on highways to save on the cost and fuel consumption and improve the

efficiency of freight operations. This practice, known as truck platooning, has unintended negative consequences on how the trucks could induce damage in the pavement infrastructure, due to the “channelized truck loading application” [Gungor and Al-Qadi 2020]. To mitigate this detrimental effect, Gungor and Al-Qadi [2020] proposed a framework to optimally randomize the pattern of axel loadings of truck platoons using V2I communication. Such a coordinated truck platooning approach entails cooperative automation among trucks and roadway infrastructure, which uniformly distributes the loadings of truck platoons over the pavement lanes, leading to an overall reduction in damage accumulation in the pavement and a longer service life of the pavement.

It is interesting to note that winter weather may induce vulnerabilities in vehicles on highways as well as in physical and digital infrastructures. For instance, the performance and reliability of CVs/AVs (and other sensors) and communications could be destabilized by extremely cold temperatures and heavy snowfall conditions, and such risks should be considered in the design of the VII system to operate in cold climates.

Conclusion And Outlook

Currently, there is an urgent demand for more cost-effective, resource-efficient and reliable solutions to address safety, mobility, and resilience challenges on highways enduring snowy winter weather. One can envisage a fundamentally changed landscape for WRM operations, traveler information, and traffic management on winter highways, amid the increasing introduction of innovative concepts (e.g., Smart Cities, Crowdsourcing, and V2X) and more penetration of emerging technologies (e.g., CVs/AVs/CATs, IoT, 5G, Cloud Computing, and Edge Computing) into the transportation sector. These concepts and technologies will catalyze the increasing momentum of VII to enable a significantly higher level of service. As such, there is the need to conceptualize and strategically plan for a more connected roadway infrastructure for VII system, even though many of the CI solutions are still in the nascent stages of development.

Driven by the paradigm shift towards more automation and more intelligent transportation, it is time to reimagine the vehicle-infrastructure ecosystem with the cold-climate issues in mind, and to enhance communications and coordination among various highway users and stakeholders. A next step is to promote the synergies among the enabling technologies and unlock their potential for the specific needs of highway agencies. For instance, CI technologies are currently less mature than CV technologies. Great benefits can be achieved by integrating the array of both CI and CV technologies. Because such integration would provide better, more accurate and timely knowledge of conditions throughout the roadway network (albeit with a focus on critical locations and road segments), in terms of traffic characteristics, RSCs, and environmental conditions. This big data could be processed, archived, and communicated to highway operators and traveling public in a timely fashion. In addition to informing travelers, such information can be fed into agency decision support tools such as the Maintenance Decision Support System (Ye et al. 2009, Rennie and Groeneweg 2017) to greatly benefit the roadway level of service and the overall safety, mobility, and productivity of the surface transportation system.

To inspire dialogues and synergistic collaborations among various stakeholders of the VII revolution, this commentary has underscored the need to plan, design, and engineer a multifunctional, next-generation highway infrastructure that is more intelligent, safer and more resilient and adaptive than the conventional highway infrastructure, fueled by more reliable and rapid collection, processing and communication of big data.

The challenges in achieving better safety and mobility on winter highways may continue to evolve and they must be addressed with systematic, holistic, and multidisciplinary approaches. A next step is to carry out concerted efforts in the research, development, pilot testing, and deployment of CI technologies, which needs to bring together expertise from different disciplines to transform the built highway environment to one that better facilitates the real-time detection of localized conditions and the flow of high-quality road weather data (e.g., V2X). The ultimate goal is to improve the safety and mobility of highways in cold climates, which in turn would translate to a broad array of social, economic and environmental benefits.

The VII revolution is still in its infancy and there are many unexplored territories and dynamics, unanswered questions, and open challenges. Innovations are much needed to overcome the various technological and institutional barriers to the successful implementation of VII system for highways in cold climates, and to maximize the synergies between the physical and digital infrastructures. It is imperative to note, however, that innovations should be anchored in answering the user requirements, i.e., following a needs-pull (vs. technology-push) approach.

Recommendations

The following presents some research needs identified in the arena of CI:

- Tap into recent advances in various V2X and ICT technologies and investigate better compatibility, automation, and integration among them, to provide the best possible road weather information, in terms of spatial and temporal resolutions, reliability, and so on. The efforts may be in the aspects of system design [Li et al. 2019, Muller 2012], hardware, and software and should take into account the given constraints of cost, communications speed and reliability, etc. as well as the specific performance requirements and functionalities needed by the VII system. The objective is to have a cohesive and affordable VII system that operates efficiently and reliably during disruptive weather of snow and ice.
- Address the technical and non-technical challenges vis-à-vis scalability, interoperability, privacy and security, in anticipation of increased number and heterogeneity of smart devices and immense amount of sensor data available, similar to those hindering the implementation of Smart City services and applications [Balakrishna 2012].
- Investigate the transformation of physical roadway infrastructure for the needs of VII applications, build resilience into highways, and tap into the opportunities of improving the design, health

monitoring and diagnosis, preservation, and utility of roads, bridges, tunnels, culverts, and RIAs, while reducing their life-cycle cost and environmental footprints.

- Develop and demonstrate technologies that can reliably supply cost-effective energy for roadways in remote, off-grid areas. A promising approach could be the hybrid use of PEHs and pyroelectric materials. Future research should focus on achieving balanced performances in energy output and cost-efficiency, reliability and resilience, durability, recyclability, and sustainability over the life cycle of the energy harvesting system. Areas of improvement may include: the selection and design of materials, PEH design (packaging, composite configuration of elements, etc.) and power electronics, optimized as a function of given traffic patterns, in-service environmental conditions, and specific energy requirements of the CI application.
- Develop and demonstrate a set of cost-effective, durable asphalt pavement mixtures or surface layers that enable reliable real-time detection of key vehicle flow parameters and other functionalities such as *in situ* anti-icing, sensing of the surface condition (dry, wet, snowy, icy, etc.) and/or sensing of the overall health condition of the pavement itself.

Abbreviations

ADAS: advanced driver assistance; ARC-IT: Architecture Reference for Cooperative and Intelligent Transportation; AVL: automatic vehicle location; CATs: connected and autonomous trucks; CAVs: connected and autonomous vehicles; CI: connected infrastructure; CV: connected vehicle; DMS: dynamic message sign; DSRC: dedicated short-range communications; ESS: environmental sensing station; FAST: fixed automated spray technology; FHWA: Federal Highway Administration; GPS: global positioning system; HAP: hydronic asphalt pavement; ICT: information and communications technology; IoT: Internet of Things; ITS: intelligent transportation system; PEH: piezoelectric energy harvester; LiDAR: Light Detection and Ranging; LTE: Long-Term Evolution; OBU: onboard unit; PP-TEG: pipe-pavement thermoelectric generator; RIA: roadside infrastructure asset; RSC: road surface condition; RSU: roadside unit; RWIS: road weather information system; TCPS: transportation cyber-physical system; TMC: transportation management center; V2I: vehicle-to-infrastructure; V2X: vehicle-to-everything; V2V: vehicle-to-vehicle; VII: vehicle-infrastructure integration; VVLC: vehicular visible light communication; USDOT: U.S. Department of Transportation; WAVE: wireless access in vehicular environments; WiMAX: Worldwide Interoperability for Microwave Access; WRM: winter road maintenance.

Declarations

Availability of data and materials

All data have been presented in the Commentary.

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Contributions

XS contributed solely to this commentary.

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Ethics declarations

Competing interests

The authors declare that they have no competing interests.

Other Declarations

- Ethics approval and consent to participate: not applicable
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