ELIMINATING BARRIERS TO CONNECTED/AUTONOMOUS VEHICLES (CAV) TECHNOLOGIES: HOW TO ASSESS THE READINESS OF EXISTING INFRASTRUCTURE

The race for transportation automation and mass deployment of Connected and Autonomous Vehicles (CAVs) technology is on the rise, especially due to their perceived social and economic benefits. CAV technologies are expected to create a paradigm shift that is urged by global socio-economic and environmental megatrends to enhance traffic safety, mobility, economic competitiveness, supply-chain efficiency, and air quality (AASHTO, 2020; European Commission, 2019). The United Kingdom, European Union, Australia, China, and the United States (U.S.), have adopted national visions and roadmaps to meet the needs of CAVs, through synchronized research, standards development, and pilot deployments (AASHTO, 2020; Australian Government, 2020; Australian Transport and Infrastructure Council, 2019; European Commission CORDIS, 2019; Zenzic, 2019). With recent breakthroughs in CAV technologies and available self-driving vehicle solutions (Elliott et al., 2019; Tesla, 2020; Waymo, 2020), public and private agencies, and infrastructure owners/operators (IOOs) started contemplating *what is the role of infrastructure in automation?* and *How do we prepare for autonomous vehicles?* (3^{MT}, 2020; AASHTO, 2020; NACTO, 2019; NCHRP, 2020; Transport Canada, 2020; US DOT FHWA, 2020; US DOT National Science and Technology Council, 2020). Questions that, without doubt, require a shared vision and collaboration between involved stakeholders, including IOOs and the automotive industry (AASHTO, 2020; NCHRP, 2020; US DOT FHWA, 2020).

Recent initiatives by the U.S. government brought together representatives from the IOOs, automotive industry, and academia to define the infrastructure role in automation, and the transformational changes required to prepare roadways for CAVs 'readiness' (AASHTO, 2020; NCHRP, 2020; US DOT FHWA, 2020). These studies include but are not limited to, the recently published reports by the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO, 2020; NCHRP, 2020). Roadway readiness is defined as taking a proactive approach in implementing the road infrastructure changes required for CAVs, as opposed to being reactive to challenges encountered as CAV technologies are deployed. AASHTO (2020) outlined the features of readiness under five main categories. The assessment of roadway geometry, identifying locations with substandard conditions for CAVs, and deploying V2I communication infrastructure, were considered essential steps under these categories to prepare roads for CAVs.

NCHRP (2020) identified three approaches to improve roadway readiness for CAVs operations. First, enhancing a vehicle's ability to connect to the infrastructure, this was referred to as 'talking to the road'. Second, enhancing roadway infrastructure recognition by vehicle sensors, which was referred to as 'seeing the road'. Since the onus of monitoring the road is expected to shift from the 'human eyes' to the 'vehicle sensors', infrastructure operators will have to coordinate with the automotive industry to improve the capability of CAVs to effectively 'see the road' through modifying the road geometry. Third, 'simplifying the road' by modifying the geometric design to support CAVs and their uses was considered a crucial component to eliminating barriers for CAV implementation. Simplifying the road includes modifying the roadway alignment or cross-section to support CAVs' safety and performance by controlling the Operational Design Domain (ODD) of the vehicle. ODD defines the environment within which an autonomous vehicle can operate safely (Colwell et al., 2018). Research has suggested that making subtle changes to the road geometry can enhance CAVs ability to effectively monitor the driving environment. According to (NCHRP, 2020), in order to meet emerging market needs (i.e., 1-5 years) and next decade market needs (i.e., 10+ years), infrastructure design must facilitate navigation by CAVs, and navigational aids must be V2I capable. Hence, recent studies identified a gap in the current knowledge base in this area and highlighted the need for further research to remove barriers caused by the physical infrastructure and simplify the interaction between vehicle sensors and the road.

For decades, engineers have been designing roads for human drivers (AASHTO, 2011; Khoury et al., 2019; Khoury & Amine, 2019; Wang & Yu, 2019). One of the principal elements of highway geometric design is the sight distance requirement for various maneuvers (e.g., stopping sight distance, SSD; passing sight distance, PSD; and decision sight distance, DSD) (AASHTO, 2011). Sight distance is the distance along the road in front of the vehicle visible from a specific vantage point on the travel lane (AASHTO, 2011; Alberta Infrastructure, 1999). Similar to how humans visualize and react to the environment, an autonomous vehicle is equipped with several sensors that it uses to map and perceive its surrounding environment. An onboard computer system processes the collected data to detect/recognize obstacles/features, and perform the required maneuvers such as swerving, steering, stopping, or reacting to regulatory traffic signs (Elliott et al., 2019; NACTO, 2019; Tesla, 2020; Waymo, 2020). Recent studies suggest that the PRT of autonomous vehicles' computer systems is in the range of 0.5 to 1.5 seconds (Khoury et al., 2019; Khoury & Amine, 2019; Mcdonald, 2018; Saeed, 2019; Wang & Yu, 2019). Only a limited number of studies (Khoury et al., 2019; Khoury & Amine, 2019; Mcdonald, 2018; Ray, 2017; Wang & Yu, 2019) have investigated the impact of autonomous vehicles on the design of highway geometric elements. Assessing the performance of existing geometric designs under different autonomous driving scenarios is essential for validating the safety of self-driving vehicle technology (AASHTO, 2020; AMPO Working Group, 2019; NCHRP, 2020). Limited information exists on how such an assessment can be performed on a network-level while accounting for the variety in vehicles' customized sensors and processing times.

For this purpose, a simulation approach using data collected by Light Detection and Ranging (LiDAR) technologies is proposed. LiDAR utilizes laser scanning equipment, global positioning systems (GPS), and navigation technologies to obtain intensity and positional information of surrounding features. The output of the LiDAR scanning process is a rich 3D point cloud of the surveyed objects that allows the extraction and assessment of road and roadside features and can support creating an accurate representation of the environment from the collected data (Gargoum & El-Basyouny, 2019; Gargoum & El-Basyouny, 2017; Hinks et al., 2015; Laefer, 2020; Vo et al., 2019; Zhang et al., 2019). Due to its millimeter-level accuracy, cost-saving in data collection, and widespread data collection capabilities, civil engineering research has gravitated towards the use of point cloud data (Laefer, 2020; Park et al., 2007; Park et al., 2015). Moreover, current practices in road maintenance and assessment involve a tremendous amount of manual surveying work by transportation agencies. Manual surveying work is time-consuming, labor-intensive, inefficient, and suffers from low accuracy and traffic disruptions (Gargoum et al., 2017; Gargoum & El-Basyouny, 2019). To address this, government agencies have explored digitizing both their infrastructure networks and related assessment methods using state-of-the-art remote sensing technologies such as LiDAR (Gargoum et al., 2017; Gargoum & El-Basyouny, 2019).

In my research, a simulation-based approach is developed to assess the geometric design of highway segments in a scanned virtual twin of the existing infrastructure using point cloud data. CAVs are modeled using their sensor set configurations and computer system capabilities. The simulation is used in a wide range of applications and utilizes complex mathematical models and

Artificial Intelligence tools to explore the visibility and critical design conditions of the environment around the vehicle. This drive, for instance, shows one application of the tool where a Tesla Model is traversing Alberta highway segments in virtual reality using the developed platform (please follow the files' names). Locations, where the sensor vision is obstructed, are detected. At these locations, the CAV computer system would not have enough time to react when an unforeseen hazard is detected (e.g., a wildlife animal, etc.).

This simulation is the first-ever quantitative assessment of roadways design readiness for CAVs and follows recent research gaps identified by significant initiatives in the field. While this issue was only recently identified, our research group has been actively researching this apparent gap in 2018. A framework of possible countermeasures, policies, and regulations was developed to help IOOs proactively manage and regulate the deployment of CAVs. These countermeasures include, but are not limited to, details of how to improve connectivity at specific locations and how to redesign a geometric feature to meet the needs of CAVs.

CONCLUSIONS, FUTURE WORK, & CAREER PLAN

Emerging technologies, such as CAVs, are rapidly evolving at a much faster pace than the efforts by infrastructure owners and operators. In early 2020, there was an apparent increase in the number of initiatives calling for research on how to test and prepare roads for CAVs. Several directions for future research were identified through collaboration between IOOs and the automotive industry. The simulation approach developed in my research is the first to provide quantitative and performance-based guidelines to CAVs deployment while considering the recommendations of these 2020 initiatives. My in-progress and future work explore developing design guidelines for roadside features (e.g., traffic signs, clear zones, etc.) and urban roads. In urban areas, the interaction between CAVs and active modes of transportation (e.g., cyclists, pedestrians, etc.) are simulated to explore the safety performance of roads in a shared environment. To meet these new needs, the field of road design will require an interdisciplinary knowledge base combining expertise from civil, automotive, and computer engineering disciplines to meet the demands of this transformative technology. Shortly, all Canadian road design guidelines must be updated to include information about CAV technologies. It would not be surprising to see dedicated chapters on how to design roads for CAVs. Without efforts to close the gap between roadway design and CAVs technologies, Canada is at risk of losing its competitive technological and economic advantage over the next decade. I aspire to pursue a career in research and development either in Canadian academia or consulting industry in this exciting field of study.

Please refer to attachment (A) in my CV for information about academic contributions/publications, further benefits of the tool, and my recent work on COVID-19.

REFERENCES

3M™. (2020). *Solutions for the Road Ahead*. Retrieved June 19, 2020, from https://www.3m.com/3M/en_US/transportation-infrastructure-us/

AASHTO (American Association of State Highway Transportation Officials). (2011). *A Policy on Geometric Design of Highways and Streets*. Washington DC: Author

AASHTO (American Association of State Highway Transportation Officials). (2020). *The Case for a National Transportation Automation Vision and Roadmap A Report by the AASHTO National Strategy for Transportation Automation Task Force*. Washington DC: Author

Alberta Infrastructure. (1999). 3R/4R GEOMETRIC DESIGN GUIDLINES. In *Highway Geometric Design Guide* (Vol. 37, Issue August). Alberta Infrastructure.

AMPO (Association of Metropolitan Planning Organizations) Working Group. (2019). *National Framework for Regional Vehicle Connectivity and Automation Planning*. Washington DC:Author. http://www.ampo.org/wp-content/uploads/2019/04/2019-AMPO-Framework-11.pdf

Australian Government. (2020). *Preparing for Automated Vehicles*. Australian Government. Retrieved April 19, 2020, from https://www.infrastructure.gov.au/transport/automatedvehicles/preparing-for-automated-vehicles.aspx

Australian Transport and Infrastructure Council. (2019). *National Land Transport Technology Action Plan (2020-2023)*. https://www.infrastructure.gov.au/transport/land-transport-technology/files/national_land_transport_technology_action_plan_2020-2023.pdf

Colwell, I., Phan, B., Saleem, S., Salay, R., & Czarnecki, K. (2018, June). An automated vehicle safety concept based on runtime restriction of the operational design domain. In 2018 IEEE Intelligent Vehicles Symposium (IV) (pp. 1910-1917). IEEE. https://doi.org/10.1109/IVS.2018.8500530

Elliott, D., Keen, W., & Miao, L. (2019). Recent advances in connected and automated vehicles. *Journal of Traffic and Transportation Engineering (English Edition)*, *6*(2), 109–131. https://doi.org/10.1016/j.jtte.2018.09.005

European Commission. (2019). *Horizon 2020: Action Plan for the future of Mobility in Europe*. Retrieved April 19, 2020, from https://cordis.europa.eu/project/id/690732

European Commission CORDIS. (2019). *Horizon 2020: Action Plan for the Future Mobility in Europe*.

Gargoum, S. A., & El Basyouny, K. (2019). A literature synthesis of LiDAR applications in transportation: feature extraction and geometric assessments of highways. GIScience & Remote Sensing, 56(6), 864-893. https://doi.org/10.1080/15481603.2019.1581475

Gargoum, S., El-Basyouny, K., Sabbagh, J., & Froese, K. (2017). Automated highway sign extraction using lidar data. Transportation research record, 2643(1), 1-8. https://doi.org/10.3141/2643-01

Gargoum, S., & El-Basyouny, K. (2017, August). Automated extraction of road features using LiDAR data: A review of LiDAR applications in transportation. In 2017 4th International Conference on Transportation Information and Safety (ICTIS) (pp. 563-574). IEEE. https://doi.org/10.1109/ICTIS.2017.8047822

Hinks, T., Carr, H., Gharibi, H., & Laefer, D. F. (2015). Visualisation of urban airborne laser scanning data with occlusion images. ISPRS Journal of Photogrammetry and Remote Sensing, 104, 77-87. https://doi.org/10.1016/j.isprsjprs.2015.01.014

Khoury, J., & Amine, K. (2019). Highway Geometric Design Changes in Response to a Fully Autonomous Vehicle Fleet. *Transportation Research Board 98th Annual Meeting*, Washington, D.C.

Khoury, J., Amine, K., & Abi Saad, R. (2019). An Initial Investigation of the Effects of a Fully Automated Vehicle Fleet on Geometric Design. Journal of Advanced Transportation, 2019. Washington, D.C. https://doi.org/10.1155/2019/6126408

Laefer, D. F. (2020). Harnessing Remote Sensing for Civil Engineering: Then, Now, and Tomorrow. In *Applications of Geomatics in Civil Engineering* (pp. 3-30). Springer, Singapore.

McDonald, D. R. (2018). How might connected vehicles and autonomous vehicles influence 34 geometric design?. In *Proceedings of the Transportation Research Board 97th Annual Meeting* (Vol. 35, pp. 2118-21630).

NACTO (National Association of City Transportation Officials). (2019). *Blueprint for Autonomous Urbanism*. New York NY:Author. Retrieved April 19, 2020, from https://nacto.org/publication/bau2/

NCHRP (National Cooperative Highway Research Program). (2020). *Connected Roadway Classification System Development (NCHRP 20-24(112))* (Issue February). Washington DC: Author

Park, H. S., Lee, H. M., Adeli, H., & Lee, I. (2007). A new approach for health monitoring of structures: Terrestrial laser scanning. *Computer-Aided Civil and Infrastructure Engineering*, *22*(1), 19–30. https://doi.org/10.1111/j.1467-8667.2006.00466.x

Park, S. W., Park, H. S., Kim, J. H., & Adeli, H. (2015). 3D displacement measurement model for health monitoring of structures using a motion capture system. *Measurement: Journal of the International Measurement Confederation*, *59*, 352–362. https://doi.org/10.1016/j.measurement.2014.09.063

Ray, B. L. (2017). Impacts of Connected Vehicles on multi-modal Geometric Design. *Transportation Research Board 96th Annual Meeting*, Washington, D.C.

Saeed, T. U. (2019). *Road Infrastructure Readiness for Autonomous Vehicles* (Doctoral dissertation, Purdue University Graduate School).

Tesla. (2020). *Tesla Future of Driving*. Retrieved April 19, 2020, from https://www.tesla.com/en_CA/autopilot?redirect=no

Transport Canada. (2020). *Transport Canada Innovative Technologies: Automated and Connected Vehicles*. Retrieved April 19, 2020, from https://www.tc.gc.ca/en/services/road/innovative-technologies/automated-connected-vehicles.html

US DOT FHWA (United States Department of Transportation Federal Highway Administration). (2020). *Federal Highway Administration. National Dialogue on Highway Automation.* Retrieved April 19, 2020 from https://ops.fhwa.dot.gov/automationdialogue/

US DOT & National Science and Technology Council. (2020). *Ensuring American Leadership in Automated Vehicle Technologies Automated Vehicles 4.0*. *January*, 56. https://www.transportation.gov/sites/dot.gov/files/docs/policy-initiatives/automated-vehicles/360956/ensuringamericanleadershipav4.pdf

Vo, A. V., Laefer, D. F., Smolic, A., & Zolanvari, S. M. I. (2019). Per-point processing for detailed urban solar estimation with aerial laser scanning and distributed computing. *ISPRS Journal of Photogrammetry and Remote Sensing*, *155*(June), 119–135. https://doi.org/10.1016/j.isprsjprs.2019.06.009

Wang, S., & Yu, B. (2019). Impacts on the Geometric Design of Highway from Non-Autonomous To Autonomous Vehicles (L1 ~ L4). *Transportation Research Board 98th Annual Meeting*, 1–6.

Waymo. (2020). *Waymo Technology*. Retrieved April 19, 2020, from https://waymo.com/tech/

Zenzic. (2019). *UK Connected and Automated Mobility Roadmap to 2030*. Retrieved April 19, 2020, from https://zenzic.io/content/uploads/2019/09/Zenzic_Roadmap_Report_2019.pdf

Zhang, P., Vo, A. V., Laefer, D., & Porfiri, M. (2019). Optimization of a highway infrastructure design through a combined computational fluid dynamics and evolutionary algorithm framework. *Bulletin of the American Physical Society*, *64*.