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Project Title

Infrastructure Safety Support System for Smart Cities with Autonomous Vehicles

University

North Dakota State University

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Research Needs

A smart city integrates diverse sets of information and communication technologies to monitor asset condition, security, safety, service quality, and operational efficiencies, often in real time [1-3]. Smart cities are continually hosting a growing number of autonomous vehicles that can sense their environment and navigate without human input [4]. Studies anticipate that autonomous vehicles will significantly improve transport efficiencies, reduce crashes, provide smoother rides, decrease congestion, and simultaneously increase traffic flow through speed harmonization and reduced demand for roadway capacity [5-9]. The USDOT expects that autonomous vehicles could eliminate more than 90% of crashes, depending on their level of adoption [10].

Many nations such United Kingdom, France, Australia, and United States have welcomed the deployment of autonomous vehicles [11-12]. As of 2016, seven states in the United States

(Nevada, California, Florida, Michigan, Hawaii, Washington, Tennessee), along with the District of Columbia have enacted laws to support autonomous vehicle testing and deployment [13-14]. Despite this momentum and the anticipated benefits, studies show that residents hesitate to embrace autonomous vehicles primarily because of safety concerns [15]. Many expect that the full adoption of autonomous vehicles will take 50 years or longer [16]. Therefore, driverless vehicles will share the roads with human-operated vehicles for a long time. Subsequently, autonomous vehicles of various levels of automation will continue to rely on human inputs. Thus, one of the biggest challenges facing smart cities is achieving fully harmonized vehicle operation in mixed driver scenarios.

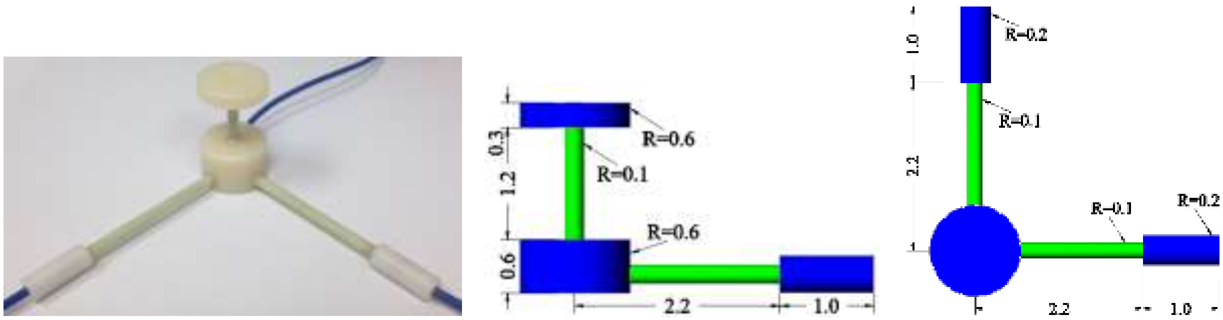
Research Objectives

1. Develop an infrastructure embedded sensor network to provide real-time traffic and road condition information such as traffic volume (e.g. ADT, peak-hour traffic), traffic composition (vehicle classification), vehicle speed, dynamic weight via weigh-in-motion (WIM), traffic density, traffic flow rate, road roughness, and other data;
2. Develop algorithms that the infrastructure safety support system will use to process the sensor-based real-time traffic data and pavement conditions to support the decision making processes of autonomous vehicles such as driving speed and safe vehicle following distances when sharing the road with human-driven vehicles;
3. Develop real-time warnings based on the data derived from the infrastructure support system;
4. Optimize the infrastructure support system such as the sensor and V2I facility layout;
5. Validate the developed infrastructure support system through simulations and field tests.

Driverless vehicles must be self-aware to make learned and ethical decisions to avoid crashes in multimodal and diverse settings. This proposed effort will develop an Infrastructure Safety Support System by embedding V2I enabled sensor networks into the transportation infrastructure to provide autonomous vehicles and human drivers with inputs to improve their decision making when obvious decisions may not possible. In addition to the four research objectives of this project, the team will use the results from this development to enhance curricula that would engage and mentor students in the practice of developing safe smart cities. This project will involve three graduate students and several undergraduate students. The trainings through this project will prepare students for potential careers in smart city developments.

Research Methods

Through a previous research project (MPC 445), the PIs' research group has developed a robust fiber optics-based infrastructure sensor for road roughness assessment. The PIs found that glass fiber reinforced polymer (GFPR) material is a good candidate to package the fiber optic sensor for improved robustness of deployment. Figures 1a, b, and c show a photograph of the sensor, including its elevation and plan view. The developed sensor has a compact size for strain measurements in three dimensions (3D). Other characteristics are a high surviving rate of up to 100% during the construction of the road, a fast data collection rate of up to 5 kHz for real-time traffic monitoring, and a long service life of up to 25 years, which aligns with the service life of pavements. In MPC 445, both the low-volume simulation loop and the I-94 mainline at MnROAD facility, MN, (shown in Figure 2a) have installed multiple of the infrastructure sensors (shown in Figure 2b, c). Field tests indicated that the developed sensors still performing well after 5 years within the pavements at MnROAD facility, MN. The infrastructure sensor network formed by these deployed sensors indicated that the infrastructure sensor network is able to provide valuable information on the road traffic and conditions, including axle weights through weigh-in-motion measurements [17, 18], and road roughness [19, 20] as shown in Figure 2d.



(a) (b) (c)

Figure 1. Geometric design of the 3D GFRP packaged fiber sensor: (a) Photo of the 3D GFRP-FBG sensor, (b) Elevation view, and (c) Plan view (Unit: in.).

(a) (b)

(c) (d)

Figure 2. MnROAD facility (a), the sensor installation scene (b), installation scene (c), and WIM measurement using the infrastructure sensor (d).

This project will continue the efforts of MPC 445 to develop a mixed driver infrastructure safety support system for smart cities based on the developed infrastructure sensor network. The team will use the infrastructure sensor network to acquire real-time traffic data, including traffic counts, traffic volume, vehicle flow rate, axle weights via high-speed WIM sensing, traffic density, and other related parameters. These real-time traffic data will be input for the development of a V2I algorithm that will harmonize the operations of autonomous and human-driven vehicles that share common facilities. The system will transmit recommended driving speed and safe vehicle following distances via the evolving V2I wireless communications infrastructure. Bluetooth radios and smartphones will communicate similar messages to human drivers.

The following provides a detailed research method to achieve each objective:

1) Dynamic driving speed recommendation: The speed of a human-driven vehicle varies with drivers, environments, and time. A sensor onboard an autonomous vehicle monitors the speed of one vehicle in front of it. Based on that information and the speed limit of the road, the autonomous vehicle will recommend a speed. If sudden events or accidents occur downstream of an autonomous vehicle, the human drivers in three to ten vehicles in front of the autonomous vehicle will respond rapidly. If monitoring only the speed of the vehicle in front of it, the autonomous vehicle will potentially create an unsafe driving situation. In addition, autonomous vehicles do not currently consider road roughness as a factor in setting their driving speed. However, road roughness is a very important factor that affects not only the level of comfort of passengers, but also the safety of vehicle operational dynamics. Infrastructure safety support systems that provide roughness information to enable the safe operation of any vehicle do not currently exist. The proposed infrastructure safety support system will provide vehicles with records of the driving speeds and vehicle classification for some optimized number of leading and following vehicles, in addition to a current road roughness. Based on the real-time detection of traffic and road roughness, the researchers will develop an algorithm to suggest the dynamic speed (V) such that:

$$V = f1\ (wi, vi, IRI) \qquad (1)$$

where wi and vi is the weight and speed, respectively, of the ith leading vehicle, and IRI is the road roughness index. The researchers will analyze the sensor data to develop the actual transfer function of Equation 1, and conduct a sensitivity study of the models developed.

2) Safe vehicle following distance recommendation: the following distance of an autonomous vehicle behind a human-driven vehicle should be a factor of the speed (vi), classification (C), and weights (WIM) of up to a certain number of vehicles in front, in addition to the road roughness. The recommend dynamic and safe following distance (L) will be in the format:

$$L = f2\ (wi, vi, C, WIM, IRI) \qquad (2)$$

The researchers will analyze the sensor data to develop the actual transfer function of Equation 2, and conduct a sensitivity study of the models developed.

3) Real-time safety warning system: the infrastructure safety support system will compare the actual driving speed and following distance of human-driven vehicles to suggest a safer driving speed and following distance. The system will issue warning signals if it detects driving speeds or following distances that are some percentage outside of the calculated safe ranges. Bluetooth radios and smartphone apps that connect to the system will communicate warning signals to human drivers.

The researchers will conduct sensitivity analysis to determine the minimum number of sensors and their deployment distances, based on the V2I algorithm developed and cost minimization criteria.

Another significant aspect of this proposal will involve the training of three graduate students in the methods of data collection, data processing, complex systems modeling, analysis, and model validation. The research findings and the theoretical development will provide a platform to develop classroom lecture and laboratory material for augmented courses in intelligent transportation systems. Furthermore, this research team will utilize the research methods and results to prepare publications and outreach material that would encourage further development towards technology transfer.

Expected Outcomes

Successful development of the proposed infrastructure support system will enable autonomous vehicles to derive information about the following:

- Real-time traffic information including traffic volume, WIM, vehicle classification, speed, flow rate, density, capacity
- Up-to-date road conditions such as road roughness
- Suggested safe dynamic speed via integrated data from the infrastructure sensor network
- Real-time safe vehicle following distance based on the infrastructure support system
- Real-time warning for human drivers in a mixed environment

This information will help autonomous vehicles and human drivers to make safer decisions instantaneously with considerations of the real traffic and road conditions, and provide the potential for safety enhancement features to implement novel warning schemes for all modes involved and manage risks based on observed trends in a mixed driver scenario.

More importantly, students will gain experience and knowledge in the multi- and inter-disciplinary aspects of computer science, mathematics, engineering, and transportation systems concepts while working with the project leaders to develop the models. The literature search and algorithm development will shape new curricula in transportation systems analysis and multimodal intelligent transportation systems. The outreach products will encourage technology transfer and piloting of complementary products.

Relevance to Strategic Goals

- Safety
- Economic Competitiveness

This study relates to the following strategic goals:

- Transportation Safety, Worker Safety, and Workforce Development – safer driving speed and following distance for autonomous and human driving vehicles in mixed environments will result in safer driving experiences for all road users, and workers. The system will increase confidence in the safety of autonomous vehicles and hasten their adoption rate to enable smart cities. Students trained will be prepared to enter a workforce that will further develop smart cities.
- Cost-effective preservation and maintenance practices for highways – agencies can use the real-time traffic and road condition information from the system to optimize repair and maintenance decisions.

Educational Benefits

This project will include at least three graduate students including one Ph.D. student and two master students each year (in total for 2 Ph.D. students and 4 master students). In addition, as the project proceeds, several undergraduate student researcher may also be involved if recruited successfully. The broader educational benefits will include curricula development in multimodal intelligent transportation systems.

Technology Transfer

This research team will utilize the developed research methods and results in this project to prepare publications and outreach material that would encourage further development towards technology transfer. Journal, conference, project process reports, and other publications will be generated through this research. Acknowledgement to this award will be made in all the related publications. Also, the PIs will notify PPPR for any publications generated from this project. If any other technology transfer product such as patents has been developed, the PIs will work with PPPR to fulfill all requirements.

Work Plan

Task 1 – Develop Infrastrcuture Sensor Network for Traffic and Road Condition Monitoring (Months 1 - 12)

1. Conduct literature search to provide an update of the present state-of-the-art
2. Derive theoretical models to obtain traffic and road condition information from infrastructure sensor networks
3. Sensitivity study on the infrastructure sensor network using simulations and lab experiments

Task 2 – Develop and Optimize the V2I Algorithms of the Infrastructure Supporting System (Months 12 - 24)

1. Develop V2I algorithms based on data derived from the infrastructure sensor network to provide autonomous vehicles and human drivers with enhanced decision-making capacity such as driving speed, vehicle spacing, and warnings
2. Perform sensitivity study on the influence of various factors in mixed driver scenario using simulations including percentage of autonomous vehicle adoption, level of atomization, etc.
3. Optimize the sensor network for maximum safety and minimum cost

Task 3 – Conduct Field Experiments (Months 24 - 36)

1. Conduct field testing on MnROAD I-94 main road with a case study
2. Validate the developed sensor network to identify traffic and road conditions in mixed driver environments
3. Validate the developed V2I algorithm of the infrastructure supporting system using autonomous vehicle prototype with a simulated mixed driver environment

Task 4 – Curricula Development and Technology Transfer (Months 24 - 36)

1. Publish conference and journal papers summarizing the study
2. Publish a project report that details the research, the findings, and conclusions
3. Incorporate results of the project into curricula development on intelligent transportation systems

Project Cost

Total Project Costs:	$564,900
MPC Funds Requested:	$282,450
Matching Funds:	$282,450
Source of Matching Funds:	North Dakota State University

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