EXECUTIVE SUMMARY

Transportation infrastructure, environment, vehicles, and users (motorists, pedestrians, bicyclists, and transit riders) must be congruously linked and interconnected, as well as interdependent, so that the transportation system can operate and be managed reliably and in good condition. However, the transportation systems of many cities in the United States are congested, unreliable, unsafe, and not resilient for at least a few hours every day. These effects could be attributed to the multifarious growth of privately-owned vehicles, the lack of access to public transportation, and inefficient public transportation infrastructure. These factors compel reliance on personal vehicles for travel, and resource constraints result in an imbalance between travel demand and capacity of the transportation infrastructure.

While affordability has contributed to an increase in the number of vehicles and to urban sprawl, recent technological advancements in the automotive industry, like hybrid vehicles and electric vehicles, have weighed on revenue generated from the gas tax and on the implementation of transportation projects. Connected and autonomous vehicles (CAVs), which encompass vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-bicyclist (V2B) communications that work in all environments and weather conditions (collectively referred to as V2X), have the potential to reduce unwanted human-driver decisions, and thus, to result in improved operational, safety and air quality performance. It is estimated that the market share of CAVs in the United States will reach up to 50% by 2040, influencing the interactions much more and at a faster pace than in the past. To account for this growth, many state and local agencies are grappling with how to balance privacy, security, safety, and legal concerns while leveraging resources to efficiently manage heterogeneous conditions.

Therefore, CAVs have drawn a lot of attention in recent years from researchers in various engineering and non-engineering fields. They include 1) mechanical/automobile engineers and electrical and computer engineers working on CAV technology, 2) transportation planners, engineers, and architects working on planning, designing, and building the transportation infrastructure, 3) geospatial and data science experts working on collecting, training, predicting, mapping, and decision-making, and 4) social scientists working on perceptions, acceptability, and impacts on society. These activities can be broadly categorized into four sub-thematic areas: 1) CAV technologies, 2) infrastructure, planning, and development, 3) information systems and connectivity, and 4) human and societal impact.

As CAV technologies hold unprecedented opportunities to shape the future of mobility, the United States Department of Transportation (USDOT) designated ten proving ground pilot sites (including one in North Carolina) to encourage CAV testing and disseminate best practices and information. CAV task forces were established in cities like Charlotte, North Carolina. Several testbeds were established nationwide. Universities are now offering relevant courses to train the next-generation's transportation development workforce, while research units on campuses have initiated funded and unfunded projects, including at UNC Charlotte.

The proposed team comprising faculty and researchers affiliated with four colleges COE, CLAS, COAA, and CCI at UNC Charlotte has the expertise as well as the complementary and multi-disciplinary skill sets to contribute to "connected autonomous mobility and infrastructure for tomorrow (CAMIT)" research. They have attracted more than $26 million in external funding in the past five years, authored more than 750 peer-reviewed publications, and advised more than 165 doctoral students. The group is highly motivated with a strong zeal to be at the forefront of CAV related research nationwide in the next three to five years, and has the potential to procure funding from the USDOT, NCDOT, Automotive OEMs, NSF, DoD, DOE, and others.

EVIDENCE OF STRENGTH AND EXCELLENCE

Strengths of the Collaboration

The team comprises faculty and researchers affiliated with COE, CLAS, COAA, and CCI. Within COE, the team comprises faculty from MEES, ECE, CEE, ETCM, and SEEM. The team includes professors, associate professors, and assistant professors. It includes registered professional engineers and Fellows of organizations such as the American Society of Civil Engineers (ASCE), Institute of Electrical and Electronics Engineers (IEEE), and Regional Science Association International (RSAI). Altogether, the team has excellent working relationships with automobile manufacturers, USDOT, NCDOT, and the city of Charlotte (DOT and Planning). As CAV research cannot be viewed from a single discipline perspective, the team plans to capitalize on its current multi-disciplinary strengths and working relationships with the public and private sectors to collaborate and submit multi-disciplinary and multi-year large grant proposals.

Evidence of the Success and Collective Impact of the Team

During the past five years, members of the team have authored/co-authored 405 peer-reviewed journal publications and 356 peer-reviewed conference publications. Overall publications by the members of this team resulted in more than 34,000 citations and Drs. Linda Xie, Chen Chen, and Jean-Claude Thill are listed in Stanford University's 2020 List as the top 2% of the world's most cited researchers. The median H-index of the group is 15; this is rather significant considering that 50% of the team members are assistant professors. Besides, the team members have authored 11 book chapters and 2 books, and 3 patents. During the last five years, the team members appeared 14 times in print and electronic media as subject matter experts.

The team members are currently serving as the editors of five journals in relevant areas, including *IEEE Transactions on Vehicular Technology*, *Fluids Special issue on Vehicle Aerodynamics and Aeroacoustics*, and *Journal of Network & Computer Applications*. Besides, team members are serving as Associate Editors of six journals and editorial board members of three journals. A number of team members served or are serving as Chairs of committees of various professional organizations that are relevant to the themes of the cluster. These include the Society of Automotive Engineers Road Vehicle Aerodynamics Committee (Uddin), American Society of Mechanical Engineering (ASME) Multifunctional Materials Committee (Xu), and the Electrochemical Energy Conversion and Storage committee (Xu). The team also includes faculty who are members of a number of standing committees.

In terms of external funding, during the last five years, the members of this group brought in $26 million through 108 grant proposals. The sponsors of these efforts include public agencies and private industries. These projects include (a) NCDOT sponsored $1 million Transportation Center of Excellence, led by UNC Chapel Hill Highway Safety Research Center, (b) a USDOT sponsored ~$7.7 million University Transportation Center led by San Jose State University, Mineta Consortium for Transportation Mobility, and (c) a $2 million “Smart and Connected Communities” grant funded by the NSF; Dr. Pulugurtha is serving as PI/co-PI on all of these grants. Another two DoE funded current projects relevant to the themes of the cluster are: (a) a $4.6 million initiative on resilient infrastructure with distributed energy resources that includes Photovoltaics and battery energy storages, and EVs; Dr. Kamalasadan is serving as the lead-PI on this consortium of two national laboratories, three universities, one industry, and one utility, and (b) a $12 million project, Dr. Xu is the UNC Charlotte lead, in collaboration with Western Michigan University, Northeastern University and Brown University, and Safescience and Nanoramics as industry partners. Industry-sponsored projects relevant to the cluster themes include four projects on edge computing for connected vehicles supported by Toyota Motor North

America (Dr. Xie), and the development of an aerodynamic package for the 2016 Viper ACR supported by Fiat Chrysler Automotive (Dr. Uddin) among others.

Additional Resources

The success of a multi-disciplinary center is fully dependent on the infrastructure and intellectual capabilities of its members. Even though the team has existing resources supporting relevant research cluster themes and sub-themes, additional infrastructure and human resources would enhance the cluster capabilities. There are only a few fully autonomous test vehicles available nationwide. As the percent of Level 1 and Level 2 CAVs owned by the public is still insignificant to make any measurable impact at present, purchase of test vehicles by UNC Charlotte would facilitate an integrated research cluster. Additionally, the team members are not aware of any testbeds with transportation infrastructure for V2X communications in North Carolina. A “smart city” testbed on the UNC Charlotte campus, or in collaboration with the city of Charlotte, would be an extremely valuable additional resource. This testbed can also be complemented with a high-fidelity state-of-the-art driver simulator. Since CAV technology and V2X communications rely on state-of-the-art computing resources, the research cluster includes tackling “big data” problems. Cloud computing databases and advanced communications are key resources. Seed funding for such resources in addition to supporting graduate students will solidify and expand ongoing efforts. On the infrastructure side, a road and grid emulator/simulation testbed with a high-performance computing cluster will be beneficial. Support for additional resources including research scholars and post-doctoral fellows will improve our capacity to innovate.

Specific Synergies of the Team

The team has several ongoing synergistic activities. Currently, the proposed cluster members have strong collaborations with more than 50 activities that include but are not limited to, joint publications, funded joint proposals, joint grant proposals, and co-supervision of research students. This shows that the group has the capability to advance the current national prominence in the proposed cluster. The cluster has a unique opportunity to attract larger funding through multi-PI holistic solution type proposals, developing into a nationally and internationally recognized center of excellence.

Contribution to Student Education and Research Training

The team has advised/mentored and graduated a total of 80 doctoral and 183 master’s students to date. The members of the proposed cluster are currently advising/mentoring 89 doctoral and 40 master’s students. Two undergraduate CLAS students have received mentoring in researching and testing privacy protocols and data collection in CAVs on-site with support from the Data Privacy Lab of Harvard University and Consumer Reports. CAMIT team members have been offering a wide range of courses for undergraduate and graduate students in the areas relevant to the proposed area of research excellence. These include Intelligent Transportation Systems, Traffic Control & Operations, Traffic Safety, Urban Analytics, Geospatial Analysis, Road Vehicle Aerodynamics, Automotive Materials, Modeling of Lithium-ion Batteries, Big Data and Artificial Intelligence: Privacy, Ethics and Law, and Intelligent and Smart Grid, etc. A number of students are also supported as Research Assistants, gaining training to work on state-of-the-art concepts. It is anticipated that these efforts will gain further momentum with the establishment of the proposed area of research excellence that promotes student involvement in interdisciplinary and multi-disciplinary research projects.

ALIGNMENT WITH REGIONAL AND NATIONAL PRIORITIES

In the United States, nearly 180 billion gallons of fuel are consumed by vehicles annually. Per the Urban Mobility Report, more than 3.3 billion gallons of fuel are wasted due to congestion, costing consumers more than $166 billion annually (>$1,000 per commuter). Additionally, more than 32,000 people are killed while 2.5 million people are injured in traffic crashes annually in the United States (of which 1,400 people are killed and over 125,000 injured in North Carolina alone). On average, a Charlotte commuter spends 57 hours a year stuck in traffic delays, and an average American commuter spends 54 hours a year stuck in traffic delays. While practitioners at national, state, regional, and local levels are striving to address the ever-increasing traffic operational and safety challenges, they also have to ensure that transportation systems are ready to support CAVs and their penetration into the market.

The global market pertaining to CAVs is expected to increase to $556 billion by 2026, with a compound annual growth rate of up to 40%. The market share of CAVs in the United States is expected to reach up to 50% by 2040. These forecasts indicate the complexity that would arise serving heterogeneous traffic conditions (CAVs and non-CAVs) while we wait to see only CAVs on roads. The substantial growth, penetration of CAVs, and new digital alliances call for a timely initiative to restructure the transportation infrastructure of cities like Charlotte, North Carolina. As CAV technology matures, state legislatures are grappling with the question of how to address safety regulations while also leveraging the opportunity for growth. Impacts include privacy, security, safety, and legal concerns, whereas opportunities include a more efficient and accessible transportation network, economic growth, and reimagining of community space allocation. A recent roadmap for CAV development (Kimley-Horn Consultants, 2016) commissioned by the NCDOT called for initiatives in all of these areas, including pilot projects and research. A similar call for the need to invest in CAV technology was made at the federal level by the USDOT in their strategic plan (USDOT, 2021). The list of prioritized research topic areas included automation, advancing emerging technologies, ensuring integration of human factors into transportation systems, and data-driven technologies, operations, and decision-making. Based on these planning documents, it is evident that DOTs at, both, the state and national level will increase research funding in areas that overlap with the expertise of the proposed R1 cluster at UNC Charlotte. The proposed team can contribute towards these areas in a meaningful and efficient way. Our diverse and esteemed colleagues are equipped with the expertise and the capability to form a collaborative research excellence cluster that can dedicate its focus towards the development of a Connected Autonomous Mobility and Infrastructure for Tomorrow (CAMIT).

The team will work to submit a proposal to USDOT for potential funding through their University Transportation Centers Grants Program. Additionally, opportunities will be explored by submitting proposals for funding from NCDOT and through the National Highway Cooperative Research Program (NCCRP). Furthermore, there are synergies with NSF’s big ideas such as “Future of Work at the Human-Technology Frontier” and “Harnessing the Data Revolution”. The team will also explore opportunities with the DOE Vehicular Technology office and also work with other national and regional agencies.

Finally, based on historic job growth, the concentration of employment, industry assets, the number of firms, and projected job growth, a recent report by the Charlotte Regional Business Alliance identified energy and automotive sectors (both of these two areas are central to the research objectives of CAMIT) as two of the four most significant industry clusters of the Charlotte region. This indicates a strong alignment of the objectives and research themes of CAMIT with the established and emerging Charlotte regional industry/business sectors.

Contribution and Expertise of the Team Members

Name	Title	Contribution and Expertise
Ahmed Arafa	Assistant Professor, Electrical and Computer Engineering	Wireless Communications, Timely Information Acquisition and Transfer, Data Privacy and Security, Statistical Signal Processing and Learning. Associate Editor: Frontiers in Communications and Networks Journal (Data Science for Communications Speciality Section).
Linquan Bai	Assistant Professor, Electrical and Computer Engineering	Modeling, operation, and planning of distribution and transmission power grids; integration of electric vehicle, energy storage and PVs; Optimization and data analytics.
Cheryl Brown	Associate Professor and Chair, Political Science and Public Administration;	Health data privacy, global policies and regulations of connected/automated vehicles, local to global privacy and ethical policies, technology acceptance and trust, data quantification and connected/automated vehicles, smart cities and privacy
Chen Chen	Assistant Professor, Electrical and Computer Engineering	Computer vision and machine learning
Amirhossein Ghasemi	Assistant Professor, Mechanical Engineering	Control Theory and Applications, Robotics, Shared Control Paradigm Designs, Optimization, Human-Machine Interaction
Tao Hong	Associate Professor, Graduate Director and Research Director, Systems Engineering and Engineering Management	Energy forecasting: wind, solar, electricity demand and price. Chair of International Institute of Forecasters Section on Water, Energy and Environment.

Jiancheng Jiang	Professor of Statistics	Data Science, Econometrics, Machine learning, and Statistics
Sukumar Kamalasadan	Professor, Electrical and Computer Engineering	Modeling of dynamic systems, control, optimization, energy storage, electric vehicle, renewable energy, power grid operation, modeling, smart grid.
Taufiquar Khan	Professor and Chair, Mathematics and Statistics	Modeling, simulation, and control using distributed parameter systems including car following models, transportation network, optimization and control with applications to model parameter estimation. Machine learning using convolutional neural networks is also a new research direction.
Minwoo Lee	Assistant Professor, Computer Science.	Machine learning. Adaptive systems. Human-AI Interactions, Distributed Learning, deep learning
Churlzu Lim	Associate Professor of Systems Engineering & Engineering Management	Architecture of Autonomous Charging Station. Operational Optimization of an Autonomous Charging Station.
Dip Maity	Assistant Professor, Electrical and Computer Engineering	Distributed control and optimization, Communication and information constrained planning and decision making, Game theory and strategic decision making, Safe and resilient heterogeneous multi-robot group control.
Dimitris Papanikolaou	Assistant Professor, School of Architecture & Software Information Systems; Director Urban Synergetics Lab	Shared Mobility on Demand Systems (planning & operations), System Dynamics, Multi Agent Modeling, Decision Support Systems, Information Visualization, Computer Supported Cooperative Work, Ubiquitous Computing, Urban Operations Research.

Srinivas Pulugurtha	Professor & Research Director of Civil & Environmental Engineering; Director of IDEAS Center	Traffic safety/operations, Intelligent Transportation Systems (includes connected & automated vehicles), transportation system planning, Geographic Information Systems applications, data analytics and visualization
Ben Radford	Assistant Professor, Political Science & Public Administration; Public Policy Ph.D. Program	Machine learning; anomaly detection; natural language processing; deep learning; computational social science; security.
Jean-Claude Thill	Knight Distinguished Professor of Public Policy; Dept. of Geography & Earth Sciences, School of Data Science, Public Policy Program	Urban planning and science, smart cities, behavioral and user acceptance, spatial modeling, machine learning
Mesbah Uddin	Professor, Mechanical Engineering; Director, Motorsports & Automotive Research Center	Road and Race Vehicle aerodynamics; Turbulence Modelling; Computational Fluid Dynamics; Data driven and reduced order flow modeling. SAE Aerodynamics Committee Chair; Editor, Fluids Special Issue on Aerodynamics and Aeroacoustics of Vehicles; Member American Institute of Aeronautics and Astronautic (AIAA) Turbulence Modeling Working Group
Andrew Willis	Associate Professor, Electrical and Computer Engineering	Robotics and autonomous systems, real-time 3D sensing, automated geometric map-building and GPS and image-based geo-localization and navigation, LiDAR, computer vision, machine learning.
Artur Wolek	Assistant Professor, Mechanical Engineering	Robots and autonomous systems; vehicle dynamics and control; collaborative path planning for connected vehicles; sensor data fusion and estimation;

Linda Xie	Professor, Electrical and Computer Engineering	Wireless communication and cloud/edge computing system support for autonomous and connected vehicles and for AI/machine learning enabled applications. IEEE Fellow; Listed in Stanford University's 2020 List as top 2% of world's most cited researchers; NSF CAREER Award (2010); 2 Best Paper Awards from IEEE/ACM international conferences; Senior Editor: Journal of Network & Computer Applications; Editor: IEEE/ACM Transactions on Networking;
Jun Xu	Assistant Professor, Mechanical Engineering;	Lithium-ion battery safety characterization, modeling and analysis; Mechanics of materials and structure designs.
Lei Zhu	Assistant Professor, Systems Engineering and Engineering Management	Intelligent Transportation System and spatial sensing (LiDAR/Camera/Radar/GPS/GIS); Smart Infrastructure and Mobility System; Big Data and Artificial Intelligence in Transportation; Traffic Simulation and Network Modeling; Connected and Automated Vehicles (CAV); Transportation Sustainability, Safety, and Electrification; Member of TRB Standing Committee on Geographic Information Science (AED40), 2020;