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INTEGRATED CONTROL OF VEHICLE SPEEDS AND TRAFFIC SIGNALS FOR REDUCING CONGESTION AND ENERGY USE

Project ID: EEMS095

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OVERVIEW



Timeline

- Project start: Dec 2020
- Project end: Sept 2023
- Percent complete: ~20%

Budget

- Total project funding: \$3,538K
 - DOE share: \$3.150K / 3 years
 - Cost share: \$388,500
- Funding for FY 2021: \$1,050K

Partners/Collaboration

- Project lead: ORNL
- CRADA with City of Chattanooga, Tennessee and Toyota Motor North America R&D
- Cubic Transportation Systems (supplier of GRIDSMART[®] system)

Barriers

- The benefits achievable with connected and automated vehicle (CAV) technologies in real-world operation, including varying traffic conditions, are not clear
 - Validation of modeling with real-world data is needed
 - Optimized controls are challenging to develop and implement for real-time operation
- Controls and communications are key factors to successful coordination of vehicle speeds with signal timing
 - Range of communications is critical factor for efficiency applications
 - Controls must function in **real time**, and in many cases vehicle-specific factors influence how effective speed control can be



ΤΟΥΟΤΑ



RELEVANCE



Overall project objective:

- Develop and demonstrate an integrated controls strategy that combines realtime traffic signal timing and vehicle speed controls in CAVs
- Validate energy consumption and traffic flow benefits through
 - 1. traffic simulation,
 - 2. dynamometer testing,
 - 3. on-road field evaluations
- Demonstrate efficiency gains of at least 15% under appropriate traffic conditions

Vehicle speed control

- Anticipate traffic signal changes \implies coordinated speeds
- Speed profile optimization: arrival at signal after red-to-green
- Traffic signal timing control, with communications to vehicles



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- Traffic signal timing control, with communications to vehicles
 - sharing of traffic information: traffic network optimization is possible
- Integration expected to yield significant benefits in travel delays, traffic smoothing and energy efficiency



RELEVANCE



- Major research questions addressed:
 - 1. What level of energy savings and traffic flow improvements can be realized from the integration of speed and traffic signal controls under different scenarios of implementation?
 - 2. How well do existing research tools predict the performance of actual control strategies and CAV systems in the real-world?
 - 3. What impact does the communication topology (direct point-to-point vs. cellular/cloudbased communications), and the corresponding communication range and signal latency, have on the performance of energy efficient mobility systems?
- Impacts:
 - Real world demonstration and validation of advanced CAVs system
 - Investigate impacts on energy and mobility for different traffic scenarios, different control strategies, and the mode of communications
 - This research will inform decisions for selection of technologies that can yield the greatest energy savings benefits as cost effectively as possible

MILESTONES



Controls development and traffic simulation evaluations (Task 1)

Month/Year	Description of Milestone or Go/No-Go Decision
June 2021	Green wave centralized speed control algorithm developed to provide speed targets for input traffic signal timing data (complete)
September 2021	Main Vissim model developed with framework for integrated speed and signal phase and timing (SPaT) controls implemented, and initial traffic simulation results obtained (on track)
December 2021	Speed control strategies developed for both centralized and distributed vehicle speed control approaches, and traffic signal timing control completed and fully integrated in Vissim model (all control strategies initiated, on track)
March 2022	All planned traffic simulations and associated analysis of benefits completed
March 2022	<u>Go/No-Go</u> : Validate that integrated speed and SPaT controls achieve 15% average energy savings of CAVs in the Shallowford Road corridor via simulation



Overview: 3 primary tasks with performance evaluations conducted at each stage using consistent methodology

Task

- Controls development and scenario evaluations via simulation (M1–M18)
- 2. CAVE Laboratory vehicle dynamometer evaluations (M12–M30)
- 3. Field evaluation (M20–M36)
- 4. Performance Evaluations (M10–36)





1. Control strategy development with microscopic traffic simulations, and communications implementation

Controls development:

- Control algorithms developed and evaluated via Vissim traffic microsimulations
- Low risk approach to demonstrate the performance of the signal timing and vehicle speed control strategies, and quantify the benefits of the integrated controls using a high fidelity traffic model of the Shallowford Road corridor, a high traffic volume business and shopping district in the city of Chattanooga, Tennessee
- Signal and speed controls implemented via APIs in Vissim: flexibility to program in Matlab, C++ or python
- Note that the communications and control strategies are linked. Several options possible for signal and speed control:
 - A. Centralized speed control (either a transient speed profile or a simple "green wave" approach) can be implemented to send speed control signals to vehicles along with controlling the SPaT parameters
 - Calculating signal timing and detailed speed profiles for all vehicles represents a strongly integrated control strategy, but it incurs very significant processing and communication demands for regular data transmission. Signal latency will also be important
 - A green wave approach has reduced communication/overall computational demands, but the control is not vehicle-specific and the efficiency benefits may be diminished as a result
 - B. Distributed speed control: each vehicle determines its own speed profile based on inputs of signal timing
 - All vehicles provide processing needed to calculate their own speed trajectory, communication required only when new information available



Controls and Communications Strategies

- How communications are implemented can have a large impact on efficiency benefits, costs, etc.
 - For vehicle speed control in response to red-green signal timing predictions, energy savings is strongly dependent on the distance before the intersection that vehicles receive signal timing data

Preview Distance (m)	Predicted Fuel Savings (L)
300	0.09
1000	0.31
3500	0.56

- Data transmission range for DSRC/CV2X is typically only around 100-200 m. Short latency generally not critical for efficiency applications
- Cellular communications enable virtually unlimited range
 - However, must determine which vehicles should receive what data, resulting in higher data management requirement

- and share traffic sensor or probe data
- Communications and data are actively managed to determine which vehicles should receive what data, based on application-specific needs

Real-Time Mobility Communications and Control System (RyThMiCCS)

Development and implementation of the communication strategy for this application will proceed in parallel with the controls development, in preparation for the on-vehicle evaluations (dynamometer and on-road)

Pipeline

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On-board web apps

RyThMiCCS is an ORNL-developed geo-spatial system with queryable database for real-time efficiencyoriented mobility control

APPROACH

- Created as a CAVs data deployment framework with extensive visualization and communication capabilities
- Big-data analytics platform to manage



Cyberinfrastructure



data/sianalzone5



2. CAVE Laboratory dynamometer evaluations

Implement speed control algorithms on Toyota prototype CAV and conduct **on-vehicle dynamometer testing**

- Safely evaluate the controls and communications in the laboratory prior to the on-road evaluation
- Complete dyno-in-the-loop evaluations of the real vehicle performance with integrated traffic signal and speed controls using ORNL's Connected and Automated Vehicle Environment (CAVE) Laboratory, which was specially developed to carry out CAV evaluations
- Simulations run in real time, while the virtual traffic signal and target speed data are transmitted to the vehicle just as in actual traffic conditions
- The CAV "thinks" it is driving in traffic and responds to the simulated SPaT and speed control signals, enabling its proper operation and performance to be measured and validated













APPROACH 3. On-Road Field Evaluation

The field evaluation will be conducted on the Shallowford Road corridor in Chattanooga

- Implementation of signal timing controls directly in the Shallowford Road corridor, with the aid of Chattanooga traffic engineers
- Test the integrated vehicle speed and traffic signal control systems under a range of traffic conditions. Traffic conditions similar to those evaluated in simulation and dynamometer testing will be evaluated during normal on-road operations
- Toyota vehicle will operate with direct speed control
- Signal timing control and speed control will be "turned off" (with normal actuated signal control being used) during portions of the testing to evaluate the system under all 4 combinations of vehicle speed control and/or traffic signal control





APPROACH 4. Performance Evaluations

Conduct detailed data analysis and performance assessments to quantify the fuel savings and mobility benefits of the integrated traffic signal and vehicle speed controls at each stage of evaluations in the project (results from Tasks 1-3). A rigorous and consistent methodology will be employed so that we both characterize the performance of the technology and validate our evaluation methods

- Using results from a) traffic simulations, b) dynamometer evaluations and c) on-road testing, complete analysis aimed specifically at quantifying fuel savings benefits, travel time reduction, and other mobility performance metrics. Additional modeling (such as Autonomie vehicle simulations, etc.) will be performed as needed to derive supplemental data needed for these evaluations
- Conduct evaluations of the traffic signal timing control and the vehicle speed control algorithms both separately and in combination to characterize the individual and integrated impacts of the controls
- Statistical evaluations will be employed for the field evaluation data, since "live" conditions are variable and not fully consistent with the simulations or dynamometer evaluations



TECHNICAL ACCOMPLISHMENTS AND SMARTMOB PROGRESS

Signal Control Algorithms

- Initial progress has been made in integrating and expanding the ORNL bilinear signal control algorithms to the Shallowford Road corridor in Chattanooga
- Preliminary results show that bilinear control strategies (based on delays and prior signal timing plan) were able to achieve comparable results but with slightly larger vehicle delays than conventional actuated signal controls
- A significant advantage of the developed control algorithms is that signal timings are known one full cycle in advance when controlled by the developed algorithms, allowing CAVs to plan longitudinal control with confidence since the uncertainties of actuated control are eliminated



TECHNICAL ACCOMPLISHMENTS AND PROGRESS

Centralized Green Wave Speed Control Algorithm Complete

- Centralized speed control algorithm determines target speed only as a function of position for all vehicles at each time
- Comparison of the spacetime diagrams for the baseline and the green wave cases shows that the simple green wave control strategy eliminates the majority of full stops throughout the simulation



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RESPONSES TO PREVIOUS YEAR REVIEWERS' COMMENTS



• New project: This is the first year that the project has been reviewed





COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

- ORNL (project leader): responsible for controls development, modeling and experimental evaluation activities
 - Controls development for integrated speed and signal timing control
 - Energy efficiency modeling/analysis
 - Vehicle dynamometer testing and powertrain controls
 - RyThMiCCS communications system development and data management
- Toyota R&D support for integration of the control strategies and communications into the prototype research vehicle; technical and commercial advisor to the project
- Chattanooga support ORNL for implementation of traffic signal controls in the on-road evaluation; provide relevant data needed for the controls development and deployment
- Cubic Transportation Systems assisting with data extraction/interpretation from the GRIDSMART[®] system (SPaT data and camera-derived traffic state characterization at intersections)

REMAINING CHALLENGES AND BARRIERS



- A variety of challenges exist for real-world implementation of any complex system. Hardware and software from different manufacturers introduces possible compatibility issues, which leads to high potential for complications
- ORNL's CAVE laboratory is being commissioned this year. Low familiarity with the equipment may lead to delays and some difficulties in performing the dynamometer evaluations
- Continued deployments at new locations in the future is complex:
 - CAV applications require standardization and compatible data and communications systems / protocols, but each location/municipality can have different equipment and constraints
 - Vehicle manufacturers' ability to broadly deploy this technology will depend on municipalities having up-to-date signal controllers and appropriate data and communications systems that employ compatible protocols

PROPOSED FUTURE RESEARCH



Plans for FY21Q4 and FY22

- Advancement of signal timing and speed control development using Vissim traffic simulations:
 - The Vissim model will be updated to include CAVs entering the corridor from all intersections and traveling in both directions so that it reflects traffic conditions that would be expected for a specified penetration rate with uniform CAVs distributions
 - The simplified 2- and 4-phase linear and bilinear signal control algorithms developed previously will be modified to create a coordinated 8-phase control algorithm that can be used to determine actual signal splits in the Shallowford Road corridor
 - The algorithms for the distributed and centralized speed control will be exercised for scenarios considering different levels of traffic congestion and varying CAV penetration rates. Simulations for a single CAV in the corridor will also be run to serve as a baseline analysis representing the on-road evaluation of the Toyota CAV. Simulations will be run with and without signal timing control to evaluate the effect of the integrated controls as well as considering each control strategy independently
 - Communication range and delay/latency for cellular and direct communications topologies will be characterized and implemented in the simulations to evaluate the difference in performance between the two communication approaches
- RyThMiCCS Communications preparations

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Implementation of vehicle detection zones and a subscription service-based communication strategy for data transfers of relevant signal data to vehicles will be developed in RyThMiCCS. This approach will be implemented to function with both virtual data (simulation results) and data feeds from real vehicles and signals, so that the RyThMiCCS communications may be used both during the dynamometer evaluations when virtual traffic conditions determine the operating state and for the on-road evaluations in Chattanooga

Any proposed future work is subject to change based on funding levels

SUMMARY



- Integrated controls for traffic signal timing and vehicle speeds can enable large gains in energy efficiency in addition to other improvements for mobility
- Details of the communications approach and control strategies employed can strongly influence the effectiveness
- In this project we are developing and demonstrating integrated signal timing and vehicle speed controls by employing a progression of evaluation methods including traffic microsimulations, lab-based dynamometer testing, and on-road evaluation of a prototype Toyota Prius Prime CAV in the city of Chattanooga, Tennessee
 - The optimized traffic signal timing controls will be deployed on the Shallowford Road corridor and evaluated under normal traffic conditions
 - Energy savings of at least 15% will be demonstrated from the integrated controls on the Toyota research vehicle, and the effects on other vehicles will be evaluated through testing and simulations
 - Methodical performance evaluations will be conducted to quantify the fuel savings and mobility benefits of the integrated control strategies at each stage of the project, which will provide direct validation of the modeling tools used for evaluation of CAV performance
 - Evaluations considering a variety of operating conditions, CAVs penetration rates, and other parameters will be evaluated



Integrated Control of Vehicle Speeds and Traffic Signals for Reducing Congestion and Energy Use

FOR MORE INFORMATION **Tim LaClair** Acting Group Leader Vehicle Connectivity & Autonomy Research Group Oak Ridge National Laboratory **laclairtj@ornl.gov**

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TECHNICAL BACK-UP SLIDES



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VEHICLE ARCHITECTURE AND DATA FLOWS FOR THE TOYOTA PRIUS PRIME CAV PROTOTYPE





TRAFFIC SIGNAL PHASE AND TIMING (SPAT) CONTROL APPROACH

- Using minimum variance stochastic control for multi-variable controls enables significant reduction in travel delays, with good computational efficiency
- Optimization for energy efficiency can be implemented, or multi-variable optimization
- Linking with vehicle speeds offers further potential for efficiency improvements



Source: H. Wang, C.R. Wang, M. Zhu, W. Hong, "Globalized Modeling and Signal Timing Control for Large-scale Networked Intersections," in Proceedings of the 2nd ACM/EIGSCC Symposium on Smart Cities and Communications (SCC 2019), Portland, OR, USA: ACM, 2019. <u>https://doi.org/10.1145/3357492.3358635</u>

SPAT-RESPONSIVE VEHICLE SPEED CONTROL

- Vehicle speed control algorithm aims to anticipate signal changes and adjust speed so arrival at signal occurs only after the green transition
- Vehicle speed reductions determined via coasting to eliminate braking
- Modified speed profile yields the same arrival time at location following the intersection, so there is no impact on travel time
- Avoiding full stop and subsequent acceleration saves considerable fuel

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A distributed approach is employed since the coasting speed profile is vehicle specific





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