Optimization, Modeling and Assessment of Smart City Transportation Systems

Hesham A. Rakha, Ph.D., P.Eng., IEEE Fellow

Samuel Reynolds Pritchard Professor of Engineering

Charles E. Via, Jr. Dept. of Civil & Environmental Engineering

Bradley Dept. of Electrical and Computer Engineering (Courtesy)

Director, Center for Sustainable Mobility, VTTI

7th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS)
10th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS)
Keynote Talk: April 29, 2021

VIRGINIA TECH TRANSPORTATION INSTITUTE

Introduction

- The world has seen significant advances in wireless communication that have made it possible for vehicles, travelers, and infrastructure to be connected
  - Connected Vehicles (CVs), Connected Travelers (CTs), and Connected Infrastructure (CI)
- In addition vehicle automation has added a dimension of vehicle control that did not exist before
  - Connected Automated Vehicles (CAVs)
- Global warming is a challenge that we collectively have to address
- This presentation describes research attempts to use CAVs and CTs to reduce the transportation system carbon footprint

ARPA-E TRANSNET PROJECT

Du J., Rakha H.A., Elbery A., and Klenk M. (2018), "Microscopic Simulation and Calibration of a Large-Scale Metropolitan Network: Issues and Proposed Solutions," 97th Transportation Research Board Annual Meeting, Washington DC, January 7-11. [Paper # 18-02086].

Elbery, A., Dvorak, F., Du, J., Rakha, H.A., Klenk, M. (2018), "Large-scale Agent-based Multi-modal Modeling of Transportation Networks - System Model and Preliminary Results," 4th International Conference on Vehicle Technology and Intelligent Transport Systems, Madeira, Portugal, March 16-18.

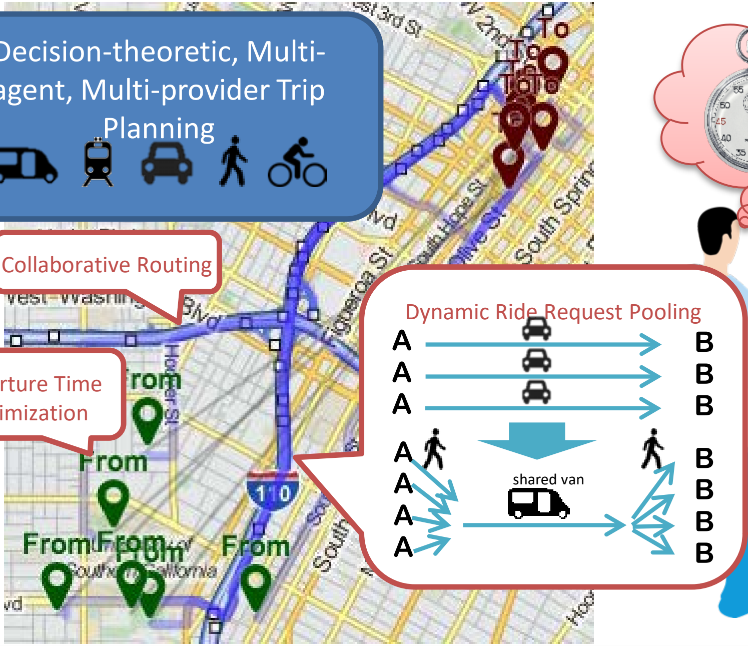
Wang J. and Rakha H.A. (2018), "Longitudinal Train Dynamics Model for a Rail Transit Simulation System," *Transportation Research Part C: Transportation Research Part C Emerging Technologies*. DOI: 10.1016/j.trc.2017.10.011.

Ghanem A. and Rakha H.A. (2019), "Modeling Instantaneous Cyclist Acceleration and Deceleration Behavior," Transportation Research Board (TRB) 98th Annual Meeting, Washington DC, Jan. 13-17. [Paper: 19-00211]

Mohan S., Rakha H.A., and Klenk M. (2019), "Acceptable Planning: Influencing Individual Behavior to Reduce Transportation Energy Expenditure of a City," *Journal of Artificial Intelligence Research*.

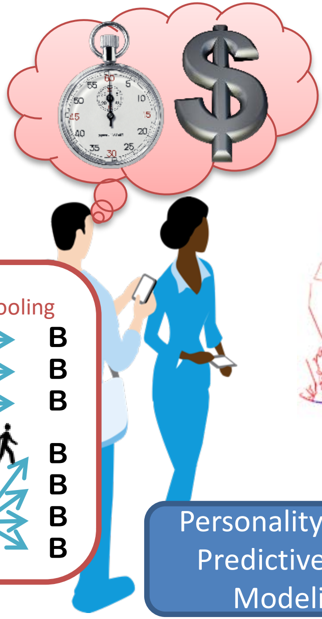
Collaborative Optimization and Planning for Transportation Energy Reduction (COPTER)

Decision-theoretic, Multi-agent, Multi-provider Trip Planning



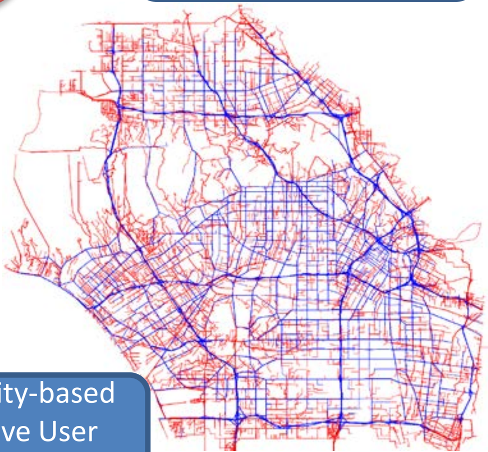
Collaborative Routing

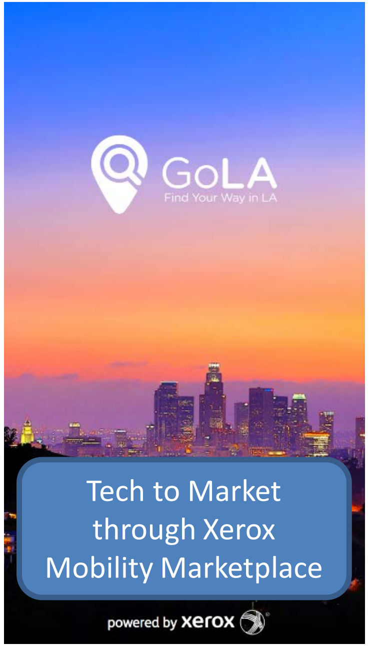
Departure Time Optimization



Personality-based Predictive User Modeling

Multi-modal Transportation and Energy Simulation





Tech to Market through Xerox Mobility Marketplace

Demonstrated: Providing the information to 10% of the travelers results in a 5.5% participation producing a 4% reduction in energy usage and 20% reduction in delay

Multi-Modal Agent-based Simulation Model

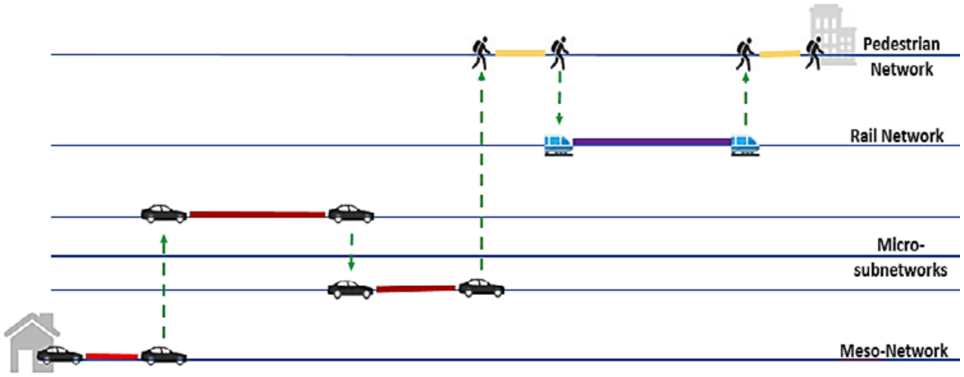
Simulation Coordinator
Tracks traveler through simulations

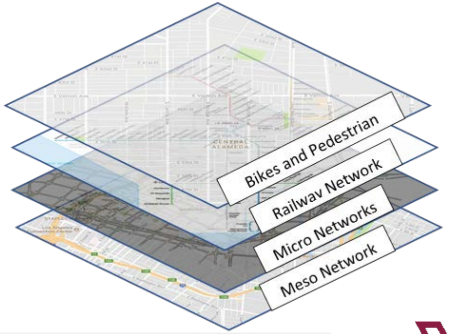
INTEGRATION
Simulates arterials and highways

MesoSim
Simulates local roads

RailSim
Simulates LA Metro Rail lines

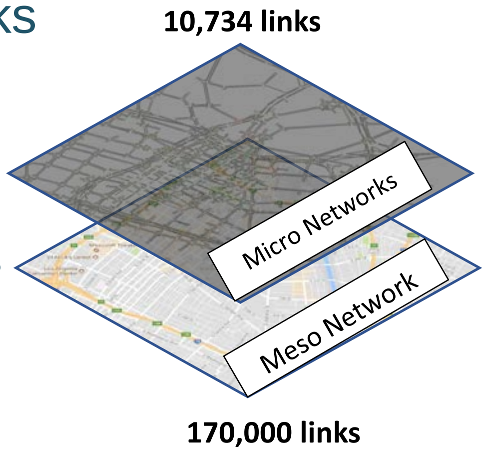
BPSim
Simulates walking and biking



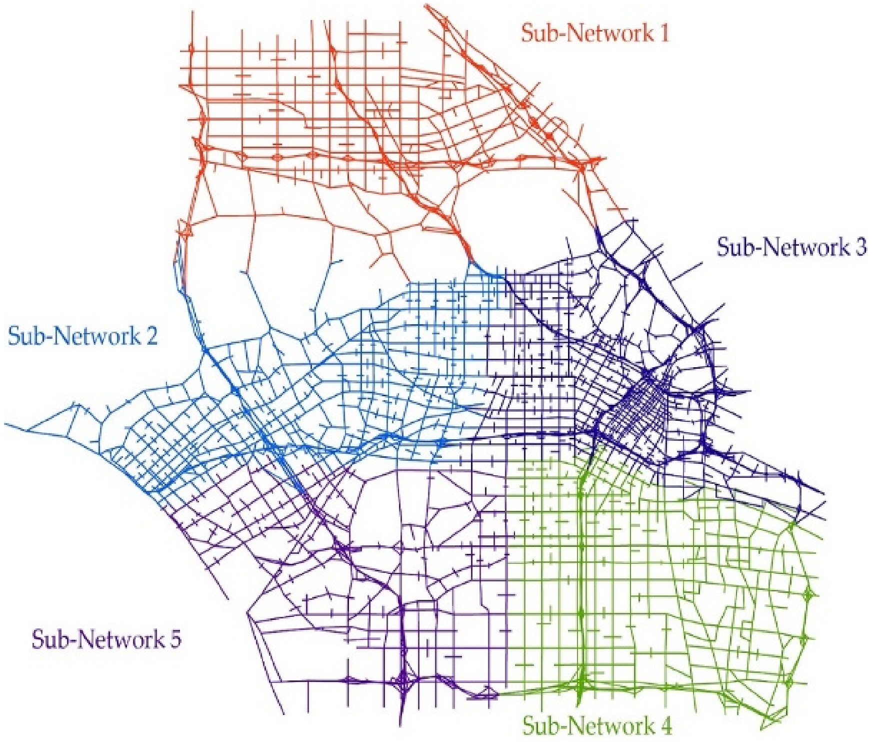


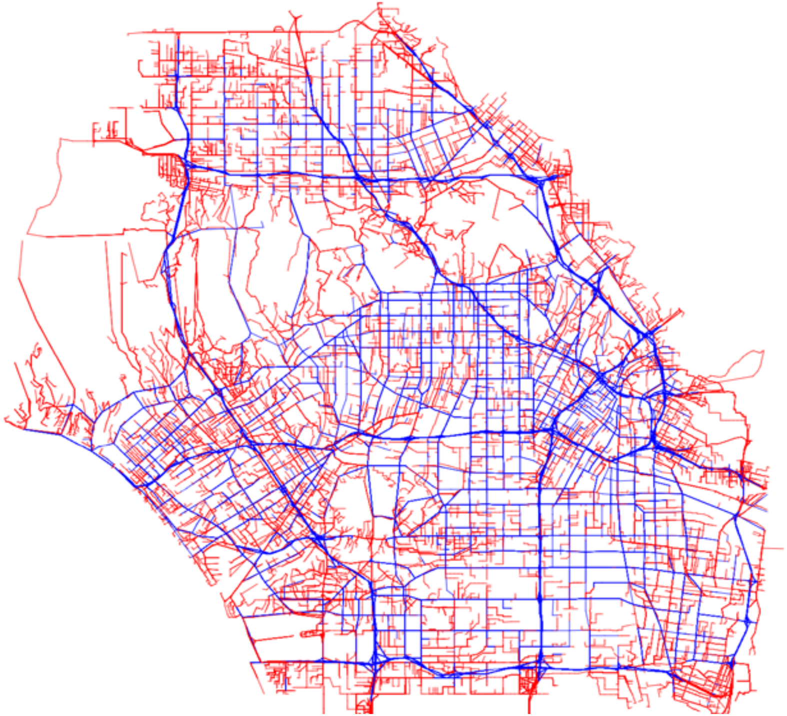
Modeling of Road Network

- The proposed model attempts to achieve high fidelity modeling of highly traveled roadways and low fidelity on other roadways
  – Computationally efficient modeling of large networks
- A hybrid simulation approach is used
  – Microscopic:
    - Enables the highest possible accuracy.
    - Models freeways, major arterials, and minor arterials
  – Mesoscopic:
    - Computationally efficient modeling of large networks
    - Used for local roads



Modeling of Road Network





Modeling of Rail Systems

- Objective:
  - Develop a longitudinal train dynamics model that captures realistic train longitudinal motion and can be calibrated without any mechanical engine data, making it ideal for implementation in microscopic transportation simulation models
- Model developed using empirical data:
  - Data from the Tri-County Metropolitan Transportation District of Oregon (TriMet).
    - Information for the Metropolitan Area Express (MAX) Blue Line where the train trajectories were collected

Wang J. and Rakha H.A. (2018), "Longitudinal Train Dynamics Model for a Rail Transit Simulation System," *Transportation Research Part C: Transportation Research Part C Emerging Technologies*.

Modeling of Rail Systems

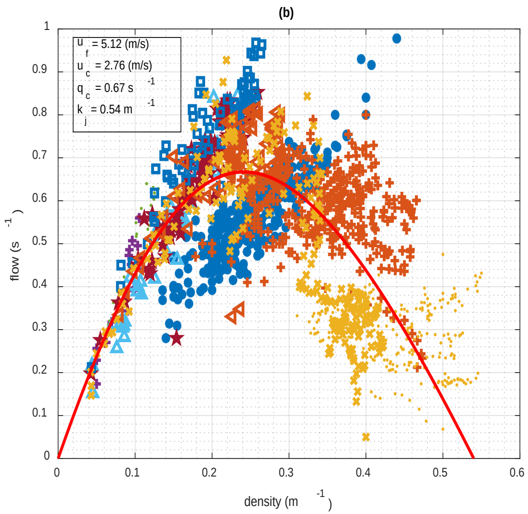
- Virginia Tech Comprehensive Power-based Energy Model (VT-CPEM)
  - Energy consumption:
    - $P(t) = \left(\frac{R(t)+(1+\lambda)ma(t)}{3600\eta_d}\right) v(t)$
  - Energy regeneration:
    - $\eta_{rb}(t) = \begin{cases} \left[e^{\left(\frac{\alpha}{|a(t)|}\right)}\right]^{-1} & \forall\, P(t) < 0 \\ 0 & \forall\, P(t) \geq 0 \end{cases}$
    - $P_B(t) = \begin{cases} \frac{P_W(t)}{\eta_D \cdot \eta_{EM} \cdot \eta_B} + P_A & \forall\, P_W(t) \geq 0 \\ P_W(t) \cdot \eta_D \cdot \eta_{EM} \cdot \eta_B \cdot \eta_{rb}(t) + P_A & \forall\, P_W(t) < 0 \end{cases}$
    - $P_W(t) = \big(ma(t) + R(t)\big) \cdot v(t)$

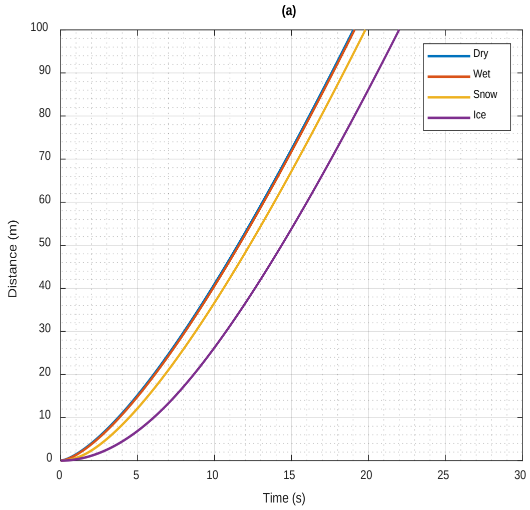
Fiori C., Ahn K., and Rakha H.A. (2016), "Power-based Electric Vehicle Energy Consumption Model: Model Development and Validation," *Journal of Applied Energy*, Vol. 168, pp. 257-268.

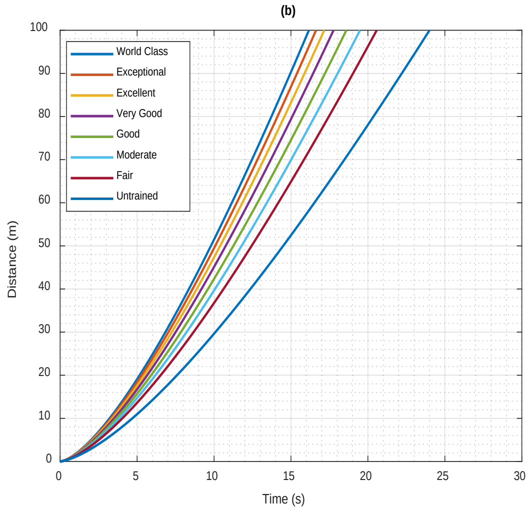
Wang J. and Rakha H. (2017), “Electric Train Energy Consumption Modeling,” Journal of Applied Energy. DOI: 10.1016/j.apenergy.2017.02.058.

Modeling Bicyclists

- Developed a dynamics-based cycling longitudinal motion model that captures cyclist training, pavement condition, gender, and grade effects.







Modeling Results

- Baseline: Driving routes planned for influenced population
- Best Case: Influenced population stays home
- CASM_1: Driving, carpooling, walking, biking, and transit routes are planned for influenced population using an assumed PQoS cost function
- CASM_2_ECO: Same as CASM_1, but all influenced driving trips are controlled by INTEGRATION’s eco-routing algorithm
- CASM_1_INF: Driving, walking, biking, and transit routes are planned for the influenced population and the actual route is determined by a stated preference influence model.

Modeling Results

Results for AM Peak/Off peak

	BASE	BEST	Mean Savings	Upper Bound	Lower Bound
Total Fuel (L)	3,195,637	2,905,967	9%	10%	8%
Total Delay (s)	897,198,320	619,162,732	30%	37.2%	24.2%

Results for PM Peak/Off peak

	BASE	BEST	Mean Savings	Upper Bound	Lower Bound
Total Fuel (L)	3,487,982	3,162,249	9.3%	10%	8.3%
Total Delay (s)	1,350,493,856	961,607,536	28.8%	32.9%	24.7%

Modeling Results

- Upper bound benefits (remove 10% of the trips):
  - 9% reduction in energy and 30% reduction in delay
- Support for a 2-4% reduction in system-wide energy through messaging 10% (5% accept the recommendations) of the population without any monetary incentives
  - Eco-routed vehicles saved 17% in energy consumption
- Eco-driving (optimizing throttle based on traffic signals and grades) does not produce benefits in highly congested areas

INTEGRATED TRANSPORTATION AND COMMUNICATION SYSTEM MODELING

1. Elbery A., Rakha H.A., ElNainay M., and Hoque M.A., (2015) "VNetIntSim: An Integrated Simulation Platform to Model Transportation and Communication Networks," International Conference on Vehicle Technology and Intelligent Transport Systems, Lisbon, Portugal, May 20-22.
2. Elbery A., Rakha H., ElNainay M., and Hoque M.A. (2015), "An Integrated Architecture for Simulation and Modeling of Small- and Medium-Sized Transportation and Communication Networks," in Smartgreens 2015 and VEHITS 2015, CCIS 579, pp. 1–22. DOI: 10.1007/978-3-319-27753-0_16.
3. Elbery A., Rakha H., El-Nainay M., Drira W., and Filali F., (2015), "Eco-Routing Using V2I Communication: System Evaluation," IEEE 18th International Conference on Intelligent Transportation Systems, Las Palmas de Gran Canaria, Spain, Sept. 15-18. [Paper # 1436].
4. Elbery A. and Rakha H.A. (2018), “VANET Communication Impact on a Dynamic Eco-Routing System Performance: Preliminary Results,” The IEEE International Workshop on Communication, Computing, and Networking in Cyber Physical Systems (CCNCPS), May 20-24, Kansas City, MO, USA.
5. Elbery A. and Rakha H.A. (2019), “City-wide Eco-routing Navigation Considering Vehicular Communication Impacts,” *Sensors*, vol. 19, no. 2, pp. 290. https://doi.org/10.3390/s19020290.
6. Farag, M.M.G.; Rakha, H.A.; Mazied, E.A.; Rao, J. INTEGRATION Large-Scale Modeling Framework of Direct Cellular Vehicle-to-All (C-V2X) Applications. *Sensors* 2021, 21, 2127. https://doi.org/10.3390/s21062127.

Integrating Transportation and Direct C-V2X Communication Modeling

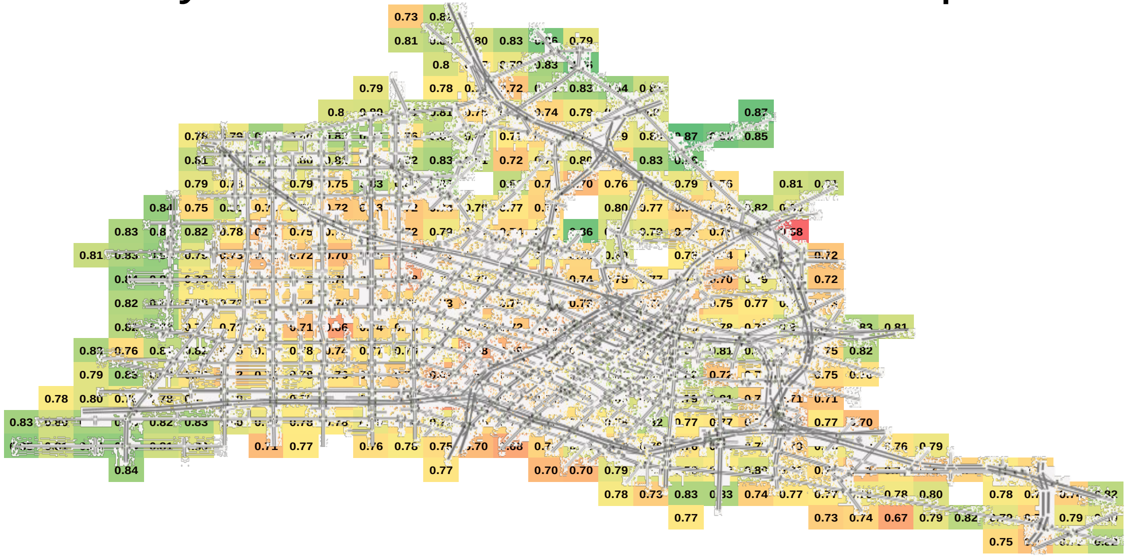
- Current communication tools are slow and not scalable
  - Auto manufacturer modeled around 2000 vehicles traveling along a highway
    - Traffic mobility and communication modeling were decoupled
      - The simulation took several days to model 20 to 50 seconds of vehicle trajectories
  - There is an urgent need to develop a scalable and integrated (coupled) traffic and communication modeling tool
- The proposed effort addresses this urgent need
  - We developed an integrated traffic and communication modeling tool
    - Simulated an hour of the calibrated AM peak demand in downtown LA (145,000 vehicles with up to 30,000 concurrent vehicles)
      - The simulation took 1.5 actual hours to simulate 1.86 simulated hours coupling every 1 to 30s while capturing millisecond packet and deci-second vehicle interactions

Integrating Transportation and Direct C-V2X Communication Modeling

- The key contributions of this effort are:
  - Developed a scalable analytical communication model that captures packet movement at the milli-second level
    - Existing model could not model LA peak hour demand
  - Coupled the communication and traffic simulation models in real-time to develop a fully-integrated dynamic modeling tool
    - Each model runs at a different modeling frequency
      - Communication model abstraction runs at 1000Hz and simulation runs at 10Hz
  - Model coupling time step is dependent on the number of concurrent vehicles on the network
    - Ranges from 1 to 30s

Integrating Transportation and Direct C-V2X Communication Modeling

- The model computes the spatiotemporal PDR
  - Can identify communication holes and hotspots



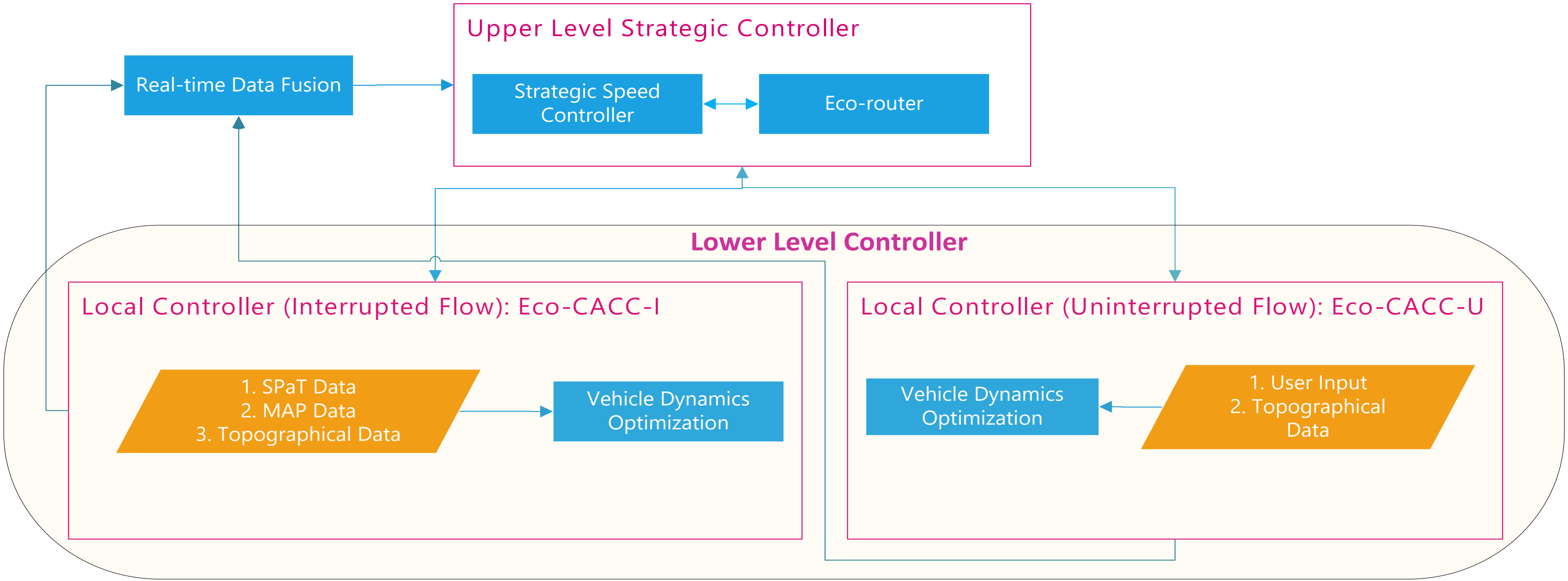
Eco-routing Application Considering DSRC Communication to RSUs

- For the ideal communication assumption, increasing the market penetration resulted in improvements in the network-wide fuel consumption levels.
  - Market penetration levels between 20% and 30% resulted in acceptable performance.
- Using realistic communication modeling showed a trade-off when increasing the market penetration of CVs.
  - At low penetration rates, the performance is acceptable because of the low packet drop rates.
  - Increasing the market penetration level results in increasing the fuel consumption because of routing errors caused by delayed and dropped data packets.
- The VANET communication network performance (packet drop and delay) can have significant effects on a dynamic eco-routing system performance, especially in highly congested networks.
  - In some cases, resulting in network-gridlock.

DEVELOPING AN ECO-COOPERATIVE AUTOMATED CONTROL SYSTEM (ECO-CAC)

1. Elbery A. and Rakha H.A. (2019), "City-wide Eco-routing Navigation Considering Vehicular Communication Impacts," *Sensors*, Volume 19, Issue 2.
2. Wang, J., Elbery, A., & Rakha, H. A. (2019). A real-time vehicle-specific eco-routing model for on-board navigation applications capturing transient vehicle behavior. *Transportation Research Part C: Emerging Technologies*, 104, 1-21.
3. Fadhloun, K., & Rakha, H. (2019). A novel vehicle dynamics and human behavior car-following model: Model development and preliminary testing. *International Journal of Transportation Science and Technology*. ISSN 2046-0430.
4. Du, J., & Rakha, H. A. (2019). Constructing a Network Fundamental Diagram: Synthetic Origin–Destination Approach. *Transportation Research Record: Journal of the Transportation Research Board*, DOI: 10.1177/0361198119851445.
5. Bichiou Y. Elouni M., Abdelghaffar H., and Rakha H.A. (2020), Sliding Mode Network Perimeter Control. *IEEE Transactions on Intelligent Transportation Systems*, ISSN 1524-9050, 1-10, DOI: 10.1109/TITS.2020.2978166.
6. Chen, H. & Rakha, H. A. (2020). Battery Electric Vehicle Eco-Cooperative Adaptive Cruise Control in the Vicinity of Signalized Intersections. *Energies*, 13(10), DOI: 10.3390/en13102433.
7. Abdelghaffar H., Elouni M., Bichiou Y. and Rakha H.A. (2020). Development of a Connected Vehicle Dynamic Freeway Variable Speed Controller. *IEEE Access*, 8, DOI: 10.1109/ACCESS.2020.2995552.
8. Wang, J., & Rakha, H. A. (2020). Empirical Study of Effect of Dynamic Travel Time Information on Driver Route Choice Behavior. *Sensors*, 20(11), DOI: 10.3390/s20113257.
9. Ahn K., Park S., and Rakha H.A. (2020), Impact of Intersection Control on Battery Electric Vehicle Energy Consumption. *Energies*, 13(12), DOI: 10.3390/en13123190.

Proposed Eco-CAC System



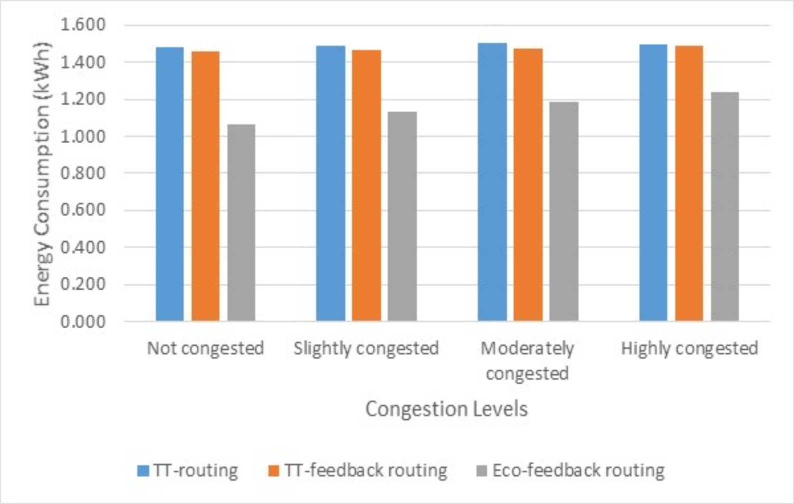
CAV Eco-routing Algorithm

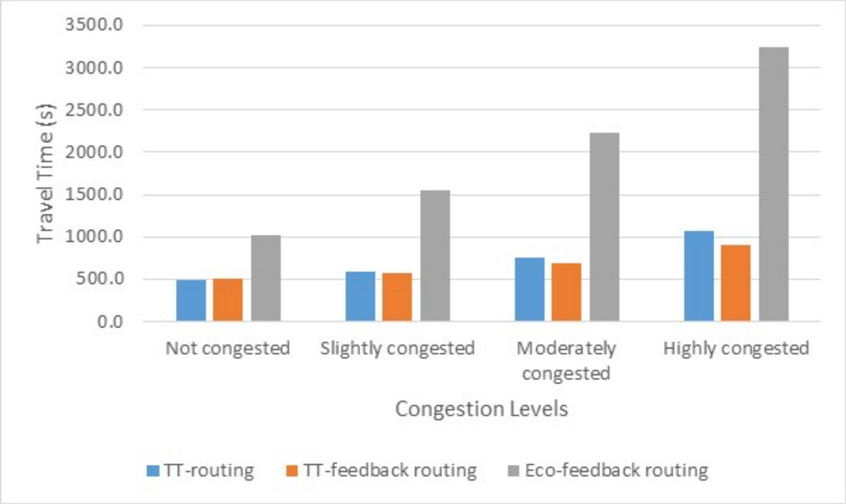
- Developed a vehicle-agnostic approach to collect transient vehicle data in real-time
  - Entire vehicle trajectory captured using 8 link-specific variables
- Data are sent to the cloud to be fused with existing data and then sent back to CAVs
  - Vehicle-specific link cost computed using the combination of vehicle parameters and the 8 link-specific variables
- Algorithm was implemented in INTEGRATION to generate
  - A dynamic, stochastic, incremental, multi-class, and user-equilibrium traffic assignment
    - Minimum paths computed using the Dijkstra algorithm

Wang J., Elbery A., and Rakha H.A. (2019), "A Vehicle-Specific Eco-Routing Model for Real-Time On-board Navigation Applications Capturing Transient Vehicle Behavior," *Transportation Research Part C: Emerging Technologies*. Vol. 104, pp. 1-21. https://doi.org/10.1016/j.trc.2019.04.017.

CAV Eco-routing Algorithm

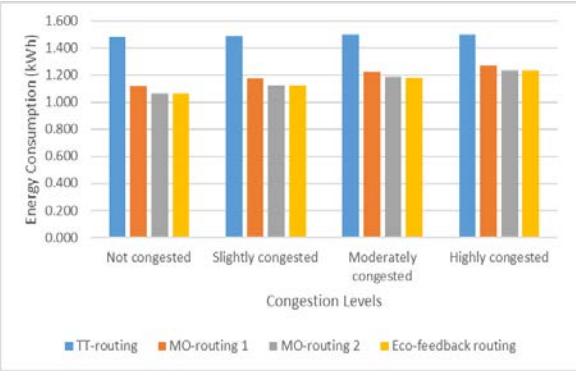
- BEV eco-routing conflicts with TT-optimum routing

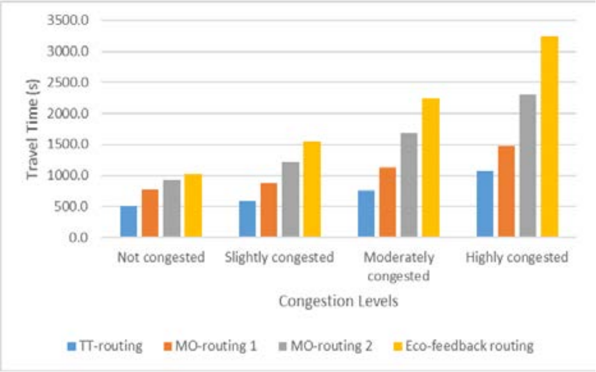


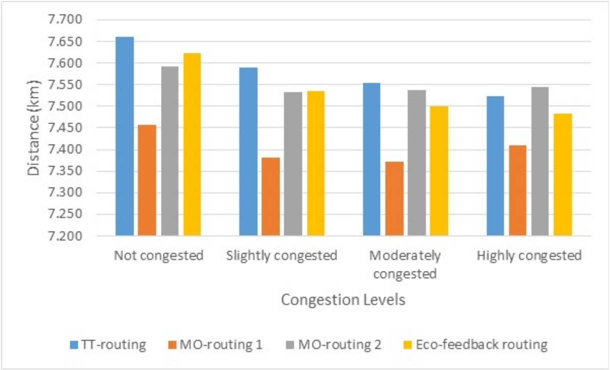


CAV Eco-routing Algorithm

- We introduced a multi-objective router that combines travel time and energy consumption
  - $C_l = (1-\alpha) \times TT_l + \alpha \times E_l \times \frac{cost\_factor}{value\_time}$
    - Considered: $\alpha = 0.01$ (MO1) and 0.05 (MO2), $value\_time$ \$10/h, $cost\_factor$ \$0.1319/kWh

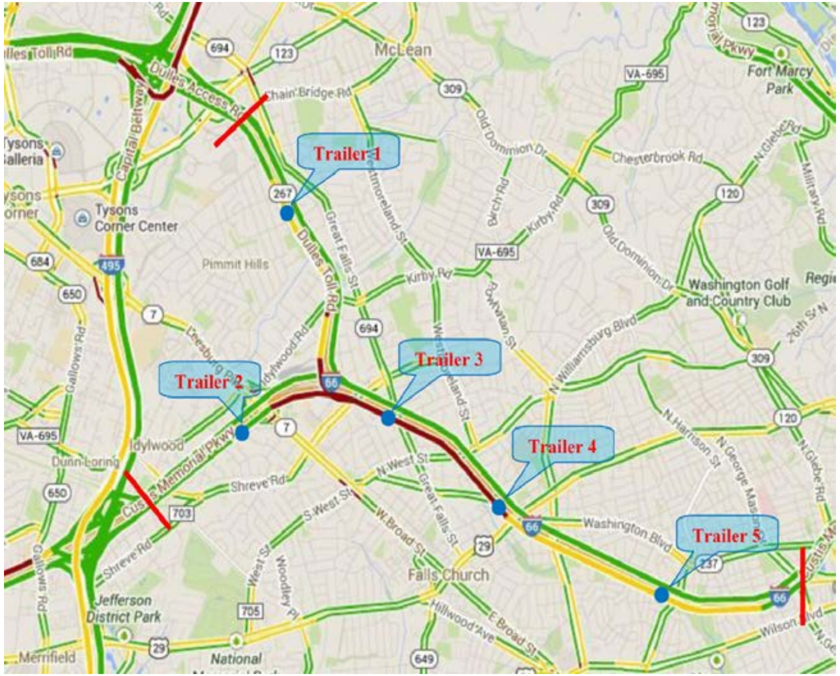






Strategic Speed Controller Field Testing

- Developed SPD-HARM algorithm
- I-66 test bed proof of concept and field testing
  - Supported Leidos and FHWA run three vehicles across all three lanes of I-66
- Conducted simulation testing considering different levels of market penetration

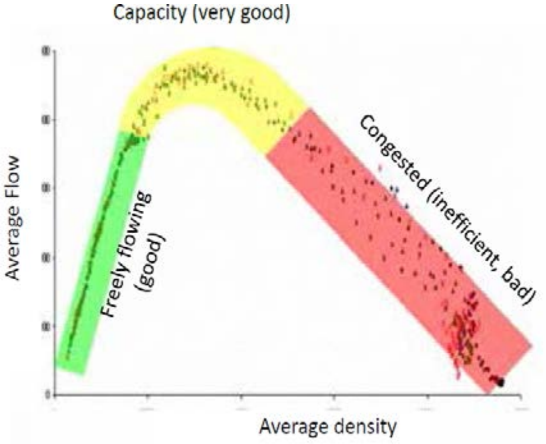


Strategic Speed Controller Testing

- The SH algorithm increases the discharge rate of the bottleneck.
  - Increases by up to 2% with reductions in vehicular delay by approximately 20%;
- The algorithm reduces vehicle emissions and fuel consumption levels.
  - At MPR=100%, CO_2 and fuel consumption can be reduced by approximately 3.5%;
- When CAV MPR is very low, benefits of the SH algorithm cannot be observed, as non-CAV vehicles do not follow the control algorithm;
  - An MPR=10% is sufficient for the SH algorithm to work successfully.
- For the study section, a CAV flow of 400 veh/h (167 veh/h/lane) is sufficient to obtain significant savings in trip delays, emissions and fuel consumption levels.

Strategic Speed Controller

- Based on network gating control using the NFD
  - Use CV data to construct NFDs
  - Identify congested regions in real-time
  - Identify gating points to control CAV speeds
  - Traffic gating using SPD-HARM
  - Integrating traffic control with dynamic routing to develop fully-integrated network controllers

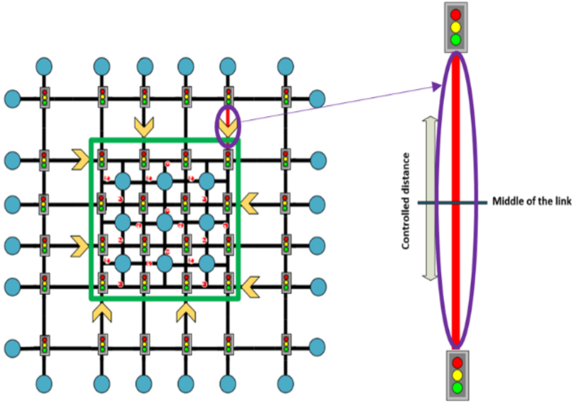


Du J. and Rakha H.A. (2019), "Constructing a Network Fundamental Diagram: A Synthetic Origin-Destination Approach," *Transportation Research Record: Journal of the Transportation Research Board*. Vol. 2673(7), pp. 478-488. https://doi.org/10.1177/0361198119851445.

Bichiou Y., Elouni M., Abdelghaffar H., and **Rakha H.A.** (2020), "Sliding Mode Network Perimeter Control," *IEEE Transactions on Intelligent Transportation Systems*. https://doi.org/10.1109/TITS.2020.2978166.

Strategic Speed Controller: Arterials

- An arterial strategic speed controller was developed that regulates the traffic stream speed upstream of traffic signals entering a protected region
  - Gating of traffic entering the protected region
  - Computation of gating rate requires an estimate of the traffic signal timings



Network-wide Performance

	No SH	SMC-SH	Improvement (%)
Avg. Travel Time (s/veh)	757.44	626.65	17.27
Avg. Total Delay (s/veh)	299.42	24.97	18.18
Avg. Stopped Delay (s/veh)	144.85	126.38	12.76
Avg. Accel/Decal delay (s/veh)	154.57	118.60	23.27
Avg. Fuel (L/veh)	0.45	0.42	5.91
Avg. CO_2 (g/veh)	1029.38	956.89	7.04

Protected Network Performance

	Improvement (%)
Avg. Travel Time (s)	15.17
Avg. queued vehicles (veh)	18.22
Total CO_2 (g)	6.68
Total Fuel (l)	6.71

Strategic Speed Controller: Freeways

- A freeway strategic speed controller was developed for use on freeways
  - Automatically identifies the onset of congestion on a roadway segment
  - Starts regulating the speed on the link upstream of the congested link
  - SPD-HARM is activated and de-activated dynamically and at different locations along the freeway

Network-wide Performance

	No SH	F-SMC-SH	Improvement (%)
Avg. Travel Time (s/veh)	1034.27	908.37	12.17
Avg. Total Delay (s/veh)	557.46	442.25	20.67
Avg. Stopped Delay (s/veh)	256.77	155.13	39.58
Avg. Fuel (L/veh)	1.16	1.12	2.60
Avg. CO_2 (g/veh)	2482.13	2400.16	3.30

Freeway Network Performance

	Improvement (%)
Avg. Travel Time (s/veh)	20.48
Avg. queued vehicles (veh/link)	21.63
Avg. CO_2 (g/link)	3.75
Avg. Fuel (L/link)	2.56

Eco-CACC-U Controller

Potential Benefits

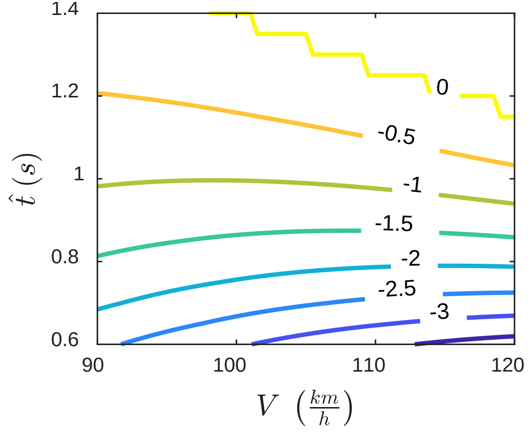
	HC	CO	NO_x	CO_2	Fuel
VT-Micro Hwy					
Top 1 %	16 %	19 %	4 %	3 %	4 %
Top 2 %	24 %	30 %	7 %	6 %	7 %
Top 5 %	39 %	47 %	17 %	13 %	14 %
Top 10 %	54 %	64 %	32 %	23 %	25 %
CMEM24 Hwy					
Top 1 %	20 %	38 %	30 %	3 %	5 %
Top 2 %	32 %	63 %	50 %	6 %	9 %
Top 5 %	52 %	80 %	73 %	14 %	17 %
Top 10 %	81 %	84 %	90 %	25 %	28 %

Eco-CACC-U Controller

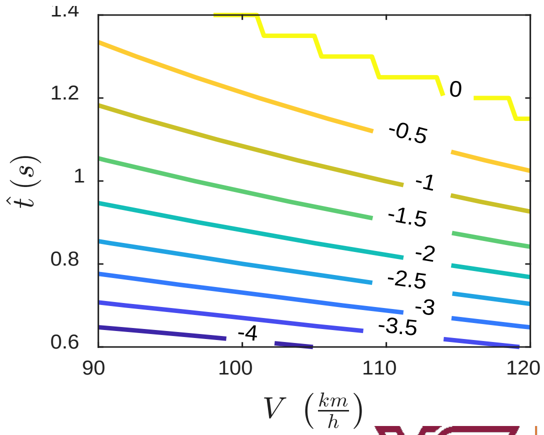
Impact of Platooning Parameters on Energy Consumption

- The behavior of ICEVs and BEVs in platoons is very different
  - Optimum speed for ICEVs is much higher than that for BEVs

ICEVs (Opt. Speed 88 km/h)



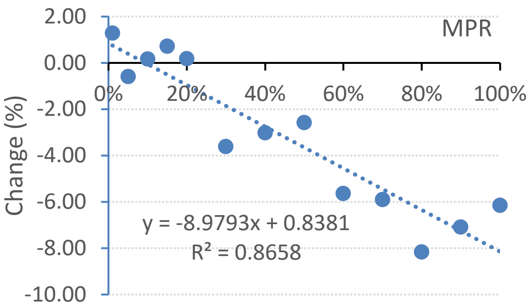
BEVs (Opt. Speed 27 km/h)



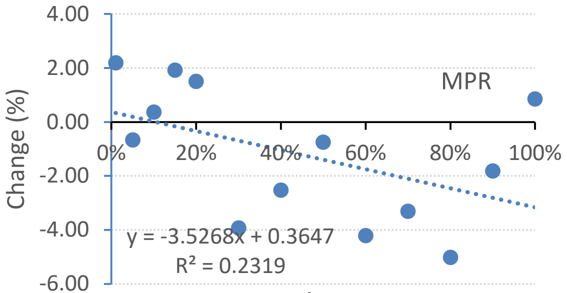
Eco-CACC-U Controller

Simulation Testing

- We developed a platooning controller that attempts to maintain relatively small time gaps between CAVs
- We assumed that a vehicle attempting to join a platoon can
  - increase its velocity by up to 7% beyond the speed limit (i.e., platooning speed) for a maximum duration of 6.5 s.



Energy Consumption



Travel Time

ECO-CACC-I CONTROLLER

Kamalanathsharma R., Rakha H. and Yang H. (2015), "Network-wide Impacts of Vehicle Eco-Speed Control in the Vicinity of Traffic Signalized Intersections," Transportation Research Record: Journal of the Transportation Research Board, Vol. 2503, pp. 90-99. DOI: 10.3141/2503-10.

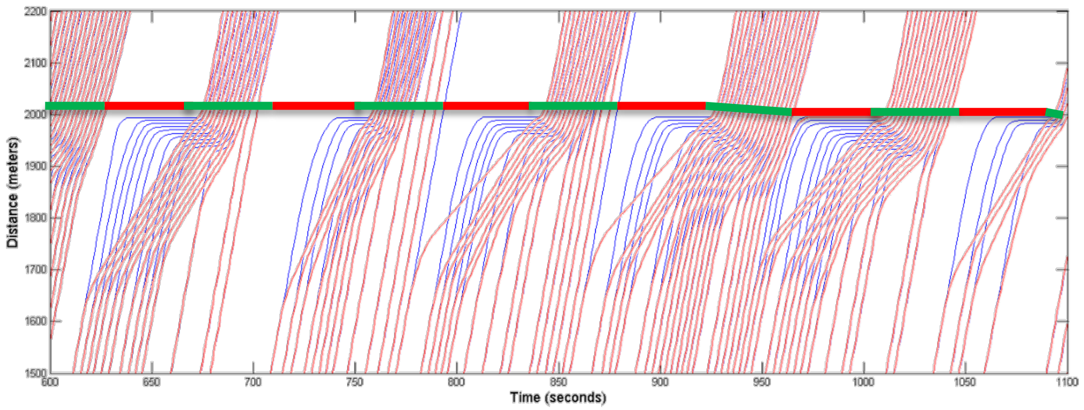
Yang H., Rakha H., and Venkat Ala M. (2016), "Eco-Cooperative Adaptive Cruise Control at Signalized Intersections Considering Queue Effects," *IEEE Transactions on Intelligent Transportation Systems*, Vol. 18(6), pp. 1575-1585. DOI: 10.1109/TITS.2016.2613740.

Almannaa M., Chen H., Rakha H., Loulizi A. and El-Shawarby I. (2017), "Reducing Vehicle Fuel Consumption and Delay at Signalized Intersections: Controlled-Field Evaluation of Effectiveness of Infrastructure-to-Vehicle Communication" *Transportation Research Record: Journal of the Transportation Research Board*, No. 2621. DOI: 10.3141/2621-02.

Almannnaa M., Chen H., Rakha H.A., Loulizi A., and El-Shawarby I. (2019), “Field Implementation and Testing of an Automated Eco-Cooperative Adaptive Cruise Control System in the Vicinity of Signalized Intersections,” Transportation Research Part D: Transport and Environment, Vol. 67, pp. 244-262. DOI: 10.1016/j.trd.2018.11.019.

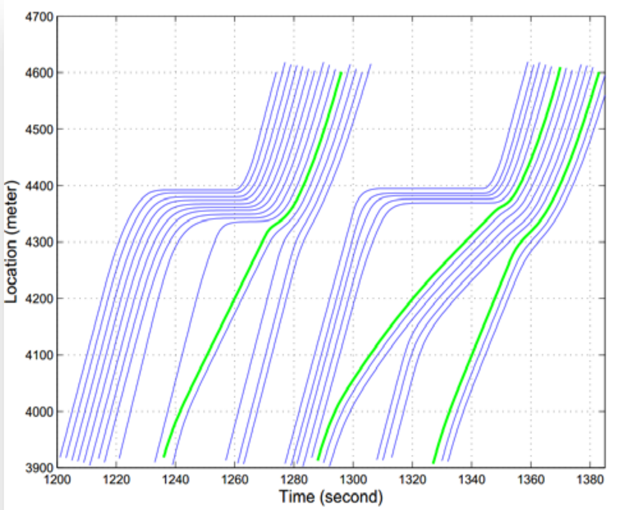
Eco-CACC-I Overview

- We developed an Eco-CACC system to compute the optimum vehicle trajectory
  - Using I2V and V2V communication
  - Explicitly optimizing vehicle fuel consumption

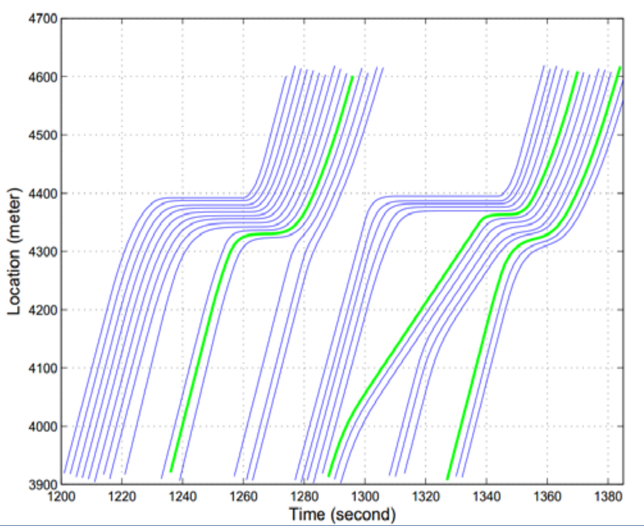


Eco-CACC-I Queue Prediction

- The model predicts the time at which the queue will be dissipated using kinematic wave theory



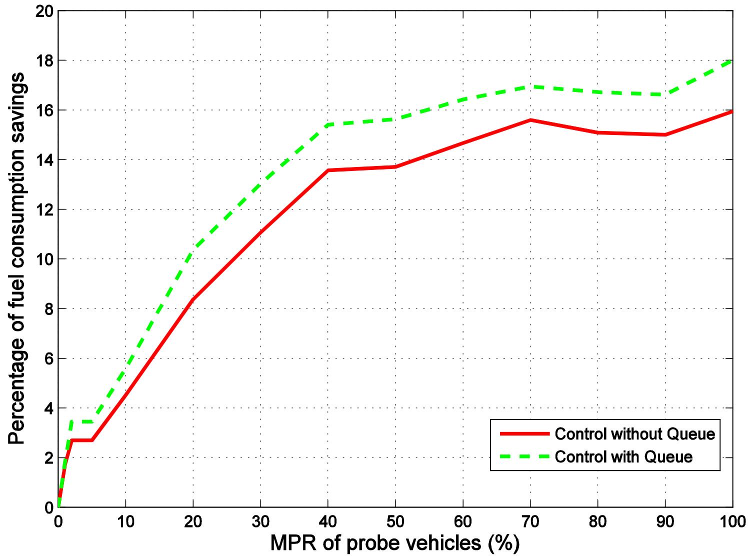
Eco-CACC with queue prediction

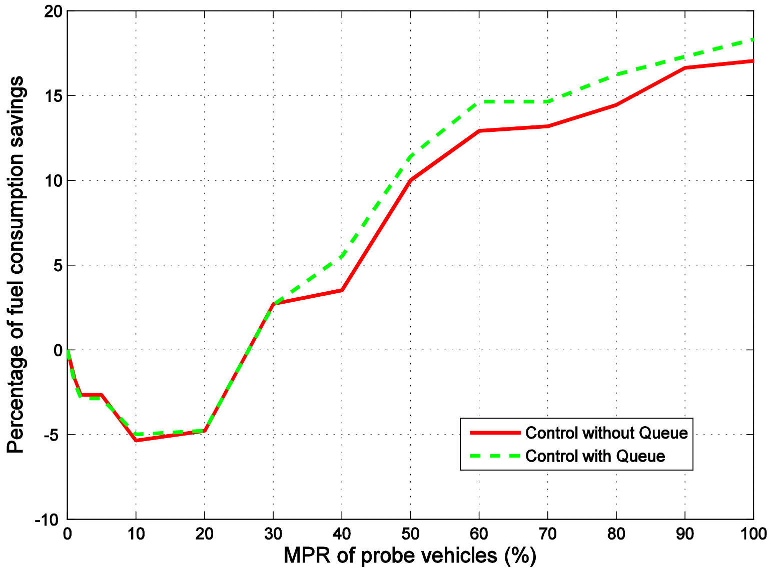


Eco-CACC

Eco-CACC-I Modeling Evaluation

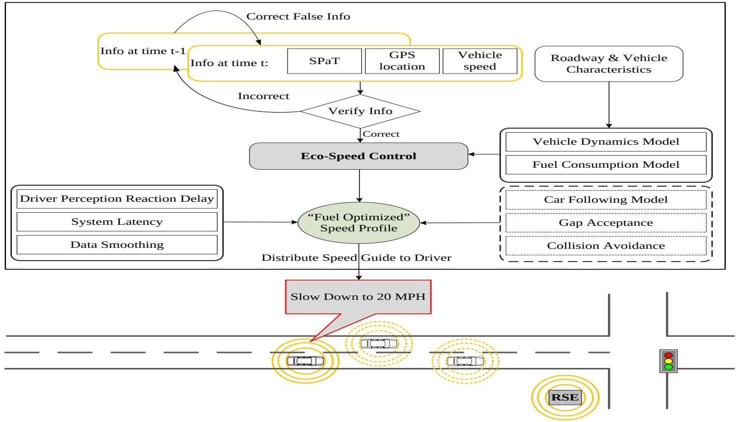
- Benefits increase with increased market penetration
- Multi-lane approaches more challenging to deal with





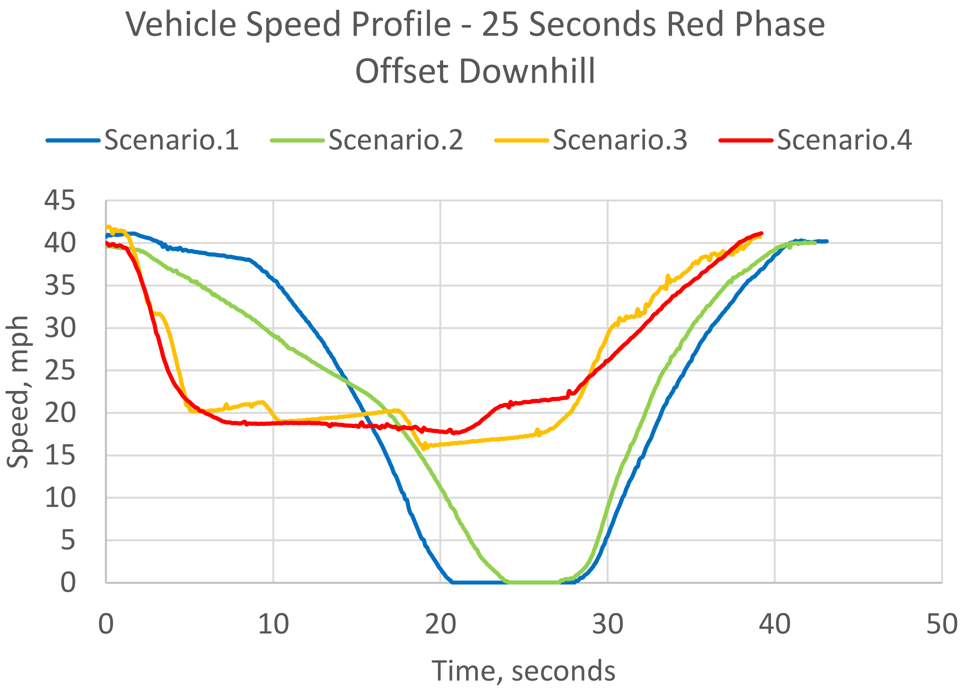
Eco-CACC-I Field Implementation and Testing

- The system was implemented in an ACC-equipped vehicle and tested on the VDOT Smart Road
  - A total of 32 subjects were recruited
    - Equal male and female participants
  - Four scenarios:
    - S1: Uninformed driver
    - S2: In-vehicle indication count-down display
    - S3: In-vehicle audio speed recommendation every 2 seconds
    - S4: L2 automation from 250m upstream of the intersection to 180m downstream



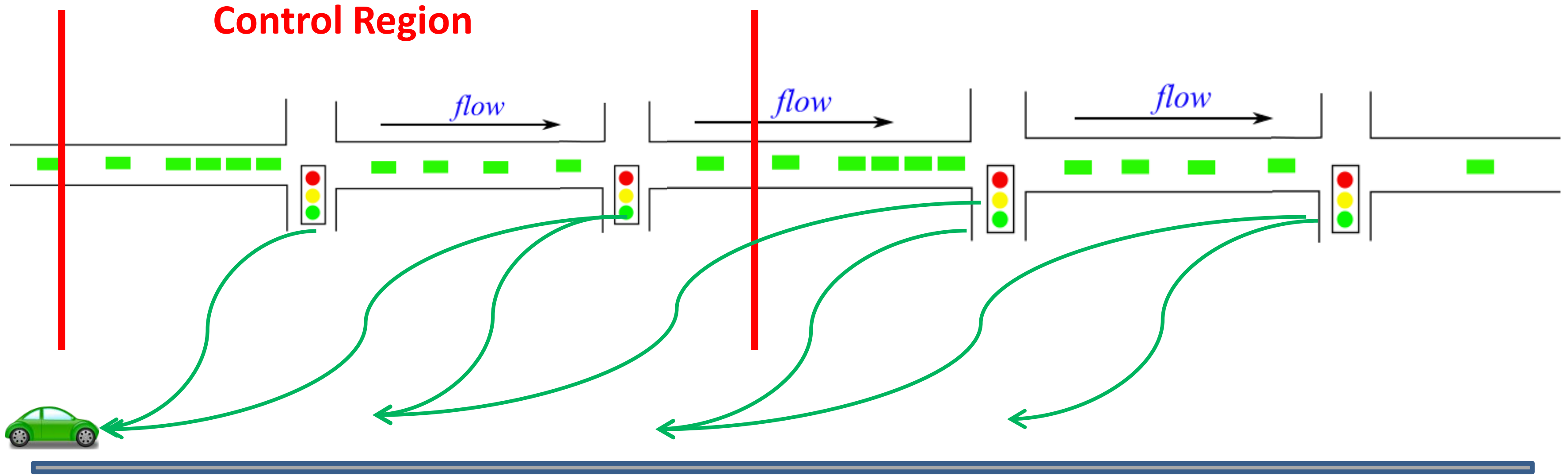
Eco-CACC-I Field Results

- The automated Eco-CACC system reduced fuel consumption levels and travel time by up to 39 and 9 percent, respectively.
- The manual Eco-CACC system reduced fuel consumption levels and travel time by nearly 13 and 9 percent, respectively.



Eco-CACC-I Considering Multiple Intersections

Yang H., Almutairi F., and Rakha H.A. (2020), "Eco-Driving at Signalized Intersections: A Multiple Signal Optimization Approach," *IEEE Transactions on Intelligent Transportation Systems*. https://doi.org/10.1109/TITS.2020.2978184.



CONNECTED VEHICLE TRAFFIC SIGNAL CONTROL

Abdelghaffar, M., Yang, H., and Rakha, H. A. (2017). Isolated Traffic Signal Control using Nash Bargaining Optimization. *Global Journal of Research In Engineering*, 16(1). https://www.engineeringresearch.org/index.php/GJRE/article/view/1516.

Abdelghaffar H., Yang H. and Rakha H.A. (2017), "Developing a De-centralized Cycle-free Nash Bargaining Arterial Traffic Signal Controller," 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems, Napoli, Italy, June 26-28.

Abdelghaffar H. and Rakha H.A. (2019), "A Novel Decentralized Game-theoretic Adaptive Traffic Signal Controller: Large-scale Testing," *Sensors*, Vol. 19(10), 2282; https://doi.org/10.3390/s19102282.

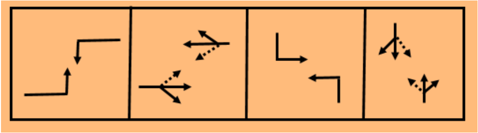
Abdelghaffar H. and Rakha H.A. (2019), "Development and Testing of a Novel Game Theoretic De-centralized Traffic Signal Controller," *IEEE Transactions on Intelligent Transportation Systems*. https://doi.org/10.1109/TITS.2019.2955918.

De-centralized Traffic Signal Control

- Developed a novel acyclic Nash Bargaining traffic signal control system
  - Objective is to control the queues on the various traffic signal approaches

$$\max_{(Q_{P1},\ldots,Q_{PN})} \prod_{i=1}^{N} (d_i - Q_{Pi})$$

$$\text{s.t.}(Q_{P1},\ldots,Q_{PN}) \in S, (Q_{P1},\ldots,Q_{PN}) \leq (d_1,\ldots,d_N)$$



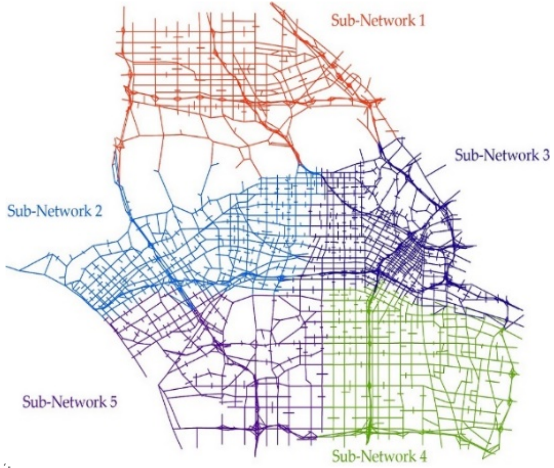
  - Abandons the concept of a fixed cycle length
    - Extends or ends various phases using the NB technique
    - Jumps directly to phases that are needed
- The **utilities** for each player (phase) can be defined as the estimated sum of the queue lengths in each phase after applying a specific action.

$$\tilde{q}_P(t+\Delta t) = \sum_{l \in P} (q_l^t + Q_{inl}\Delta t - Q_{outl}\Delta t)$$

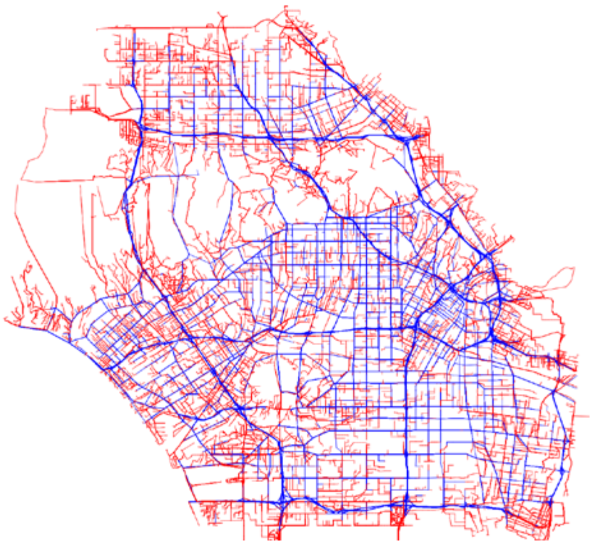
De-centralized Cycle-free Traffic Signal Controller

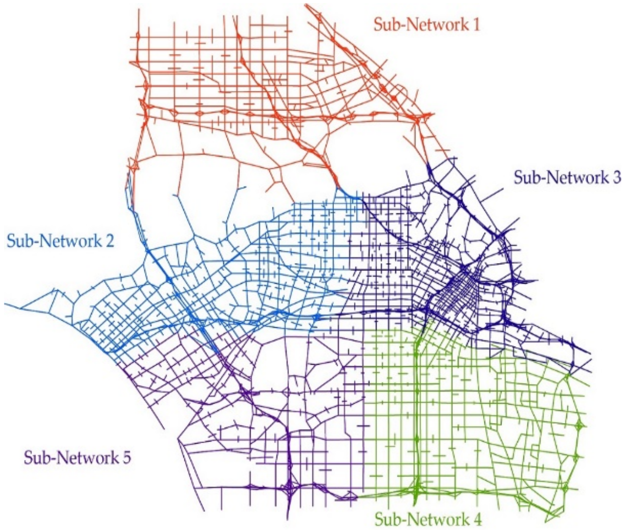
- System tested on numerous networks:
  - Main St., Blacksburg
  - Blacksburg
  - Downtown LA

MOE \ System	PSC	NB	NB Imp. (%)
Average Total Delay (s/veh)	557.463	476.346	14.55
Average Stopped Delay (s/veh)	256.766	192.116	25.178
Average Travel Time (s)	1034.27	952.732	7.89
Average Number of Stops	7.406	6.487	12.4
Average Fuel (L)	1.155	1.109	4.0
Average CO_2 (grams)	2482.13	2376.59	4.25



Int. # \ MOEs	Travel time	Queue	Num. of Stops	CO_2	Fuel	Nox
Overall 457 Int. (%)	35.156	54.669	44.031	9.966	9.919	11.774





Thank you!

Hesham A. Rakha
hrakha@vtti.vt.edu 540-231-1505

VIRGINIA TECH TRANSPORTATION INSTITUTE