# Overview of VTTI's Environmental Connected Vehicle Research Activities

VTTI Driving Transportation with Technology


By

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# Presentation Outline

- Eco-routing
  - Field and modeling results
- Eco-drive systems
- Eco-cooperative adaptive cruise control systems in the vicinity of signalized intersections
- Autonomous vehicle control
- On-going and future research initiatives

# Connected Vehicle Eco-Routing Research

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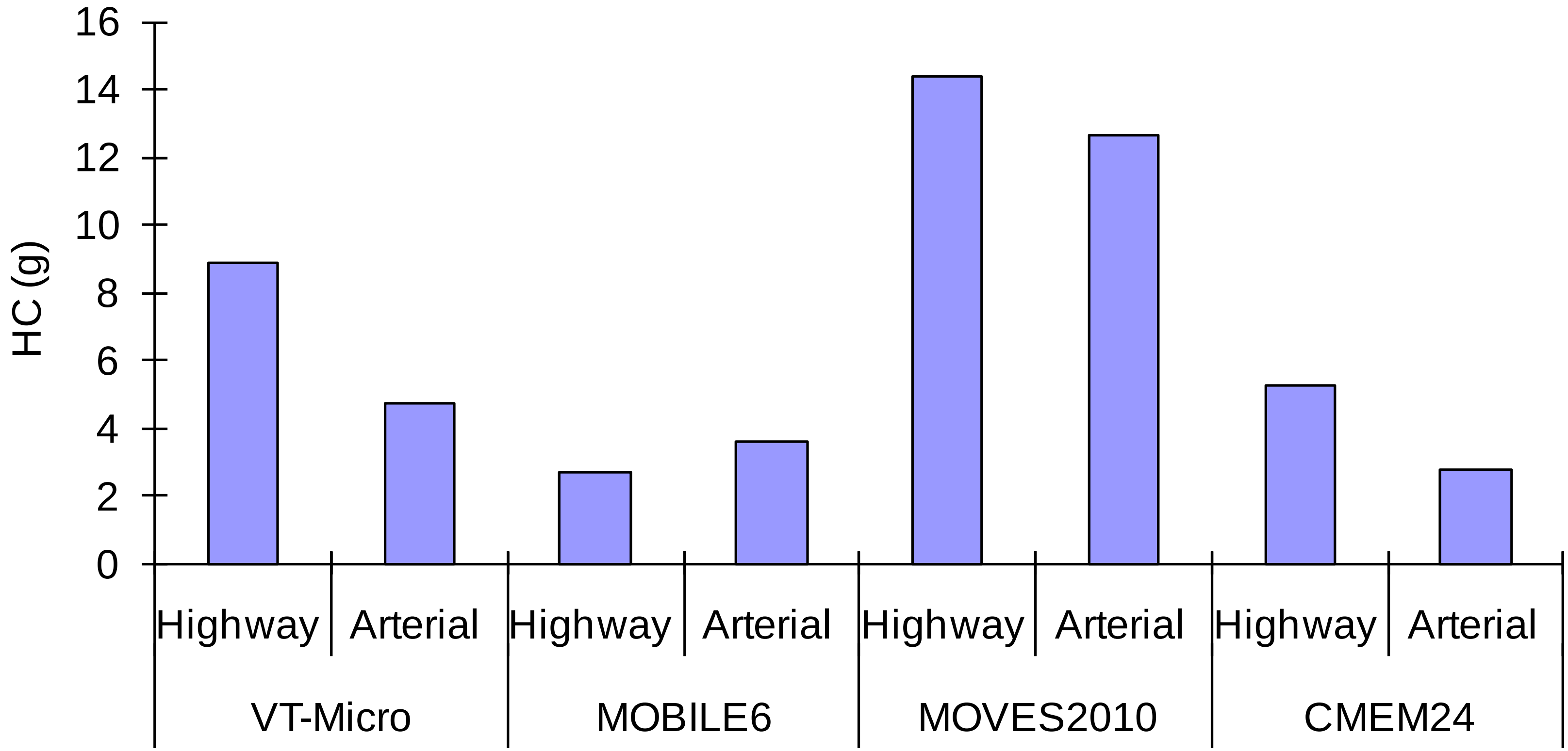
# Trip Characteristics

| | Highway | Arterial | Difference |
|---|---|---|---|
| Average Travel Time (min) | 25.63 | 29.9 | 4.27 (14%) |
| 95 percentile of Travel time | 36.25 | 37.86 | |
| 5 percentile of Travel time | 23.32 | 26.23 | |
| Std.Dev. of Travel Time (min) | 4.17 | 5.08 | 0.91 |
| Average Speed (mi/h) | 53.39 | 35.39 | 18 |
| Std. Deviation of Speed | 6.39 | 4.94 | |
| 95 percentile of Speed | 58.85 | 39.44 | |
| 5 percentile of Speed | 37.04 | 27.46 | |
| Distance (mi) | 22.44 | 17.25 | 5.19 |

Ahn K. and Rakha H. (2008), "The Effects of Route Choice Decisions on Vehicle Energy Consumption and Emissions," *Transportation Research Part D: Transport and Environment*, Vol. 13, pp. 151-167.

# HC Emissions



# Contribution of High Engine Loads

| | HC | CO | NOx | CO2 | 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 % |

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# System-wide Eco-Routing Impacts: The INTEGRATION Connected Vehicle Framework

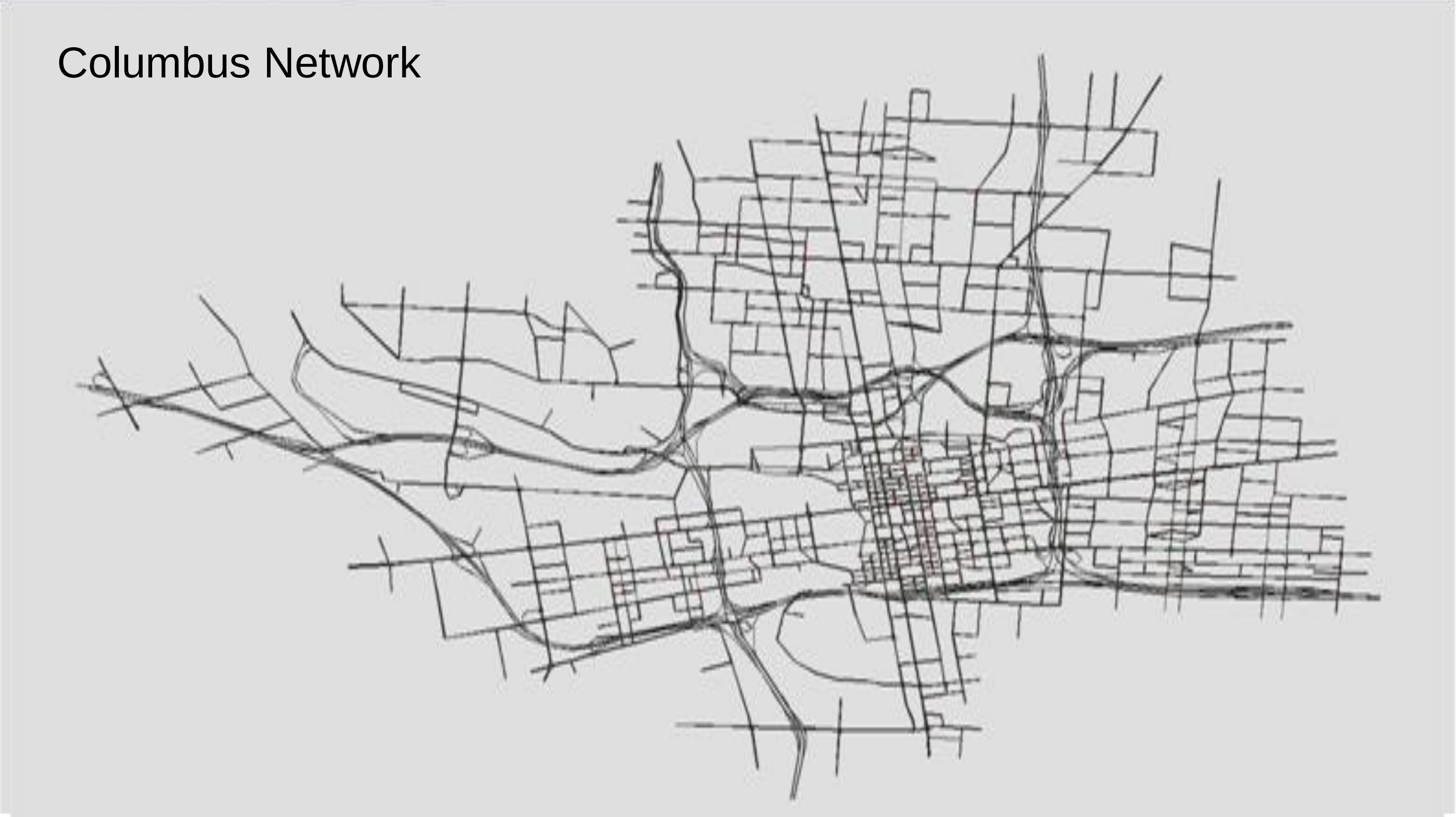
Rakha H., Ahn K., and Moran K., (2012), "INTEGRATION Framework for Modeling Eco-routing Strategies: Logic and Preliminary Results," *International Journal of Transportation Science and Technology*, Vol. 1, no. 3, pp. 259-274.

Ahn K. and Rakha H. (2013), "Network-wide Impacts of Eco-routing Strategies: A Large-scale Case Study," *Transportation Research Part D: Transport and Environment.* Vol. 25, December, pp. 119-130. DOI: 10.1016/j.trd.2013.09.006.

# Connected Vehicle Eco-routing Logic

- Model initialization:
  - Routes selected based on fuel consumption levels for travel at the facility's free-flow speed
- Feedback system:
  - Vehicles report their fuel consumption experiences prior to exiting a link
  - Moving average fuel consumption estimate is recorded for each link for each of the five vehicle classes
  - Re-routing frequency defined by user
  - Independent white noise errors can also be introduced
    - Vehicle class dependent

# Network-wide Testing



# Network Characteristics

- Cleveland network
  - Four interstate highways (I-90, I-71, I-77, and I-490)
  - 65,000 vehicles in the morning peak hour.
  - 1,397 nodes, 2,985 links, 209 traffic signals, and 8,269 origin-destination (O-D) demand pairs using 2010 demand data.
- The Columbus network
  - Three interstate highways (I-70, I-71, and I-670)
  - Grid configuration.
  - Downtown area is a bottleneck during peak hours.
  - Network provides more opportunities for re-routing compared to the Cleveland network.
  - 2,056 nodes, 4,202 links, 254 traffic signals, and 21,435 O-D demand pairs.

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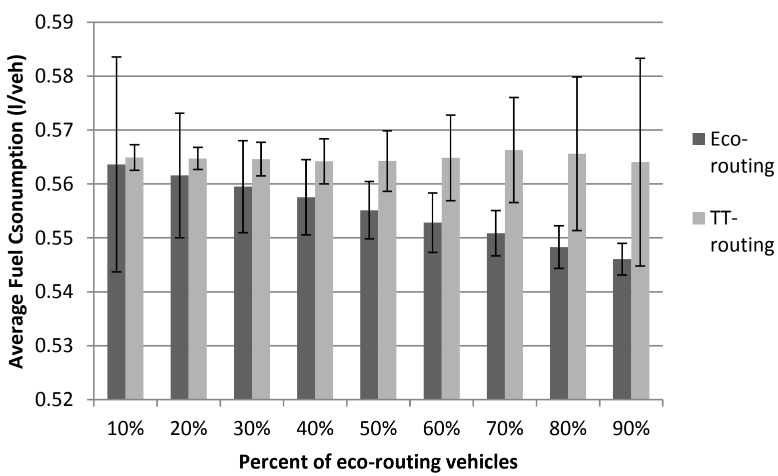
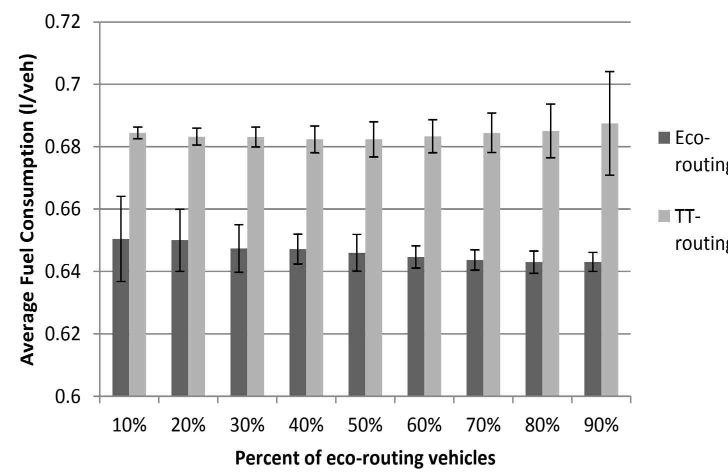
# Network-wide Impacts

- Eco-routing consistently reduces network-wide fuel consumption levels
  - Reductions of 3.3 and 9.3 percent, respectively
  - 4.8 and 3.2 percent increase in the average travel time




Cleveland




Columbus



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# Network-wide Impacts

## Impact of Traffic Demand

| MOEs | Routing Method | Cleveland 50% | Cleveland 75% | Cleveland 100% | Cleveland 125% | Cleveland 150% | Columbus 50% | Columbus 75% | Columbus 100% | Columbus 125% | Columbus 150% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance (Km) | ECO | 4.57 | 4.57 | 4.57 | 4.57 | 4.56 | 5.25 | 5.25 | 5.24 | 5.24 | 5.24 |
| | TT | 4.81 | 4.81 | 4.82 | 4.82 | 4.81 | 5.54 | 5.54 | 5.54 | 5.55 | 5.55 |
| | Rel. Diff | 5.0% | 5.1% | 5.1% | 5.2% | 5.2% | 5.3% | 5.3% | 5.5% | 5.6% | 5.7% |
| Time (s) | ECO | 312 | 315 | 317 | 321 | 325 | 316 | 320 | 323 | 328 | 335 |
| | TT | 299 | 301 | 304 | 307 | 310 | 306 | 309 | 313 | 318 | 363 |
| | Rel. Diff | -4.3% | -4.5% | -4.5% | -4.6% | -4.8% | -3.2% | -3.4% | -3.2% | -3.1% | 7.8% |
| Fuel (l) | ECO | 0.537 | 0.540 | 0.543 | 0.547 | 0.551 | 0.633 | 0.638 | 0.643 | 0.652 | 0.662 |
| | TT | 0.556 | 0.560 | 0.565 | 0.571 | 0.576 | 0.669 | 0.676 | 0.685 | 0.699 | 0.730 |
| | Rel. Diff | 3.37% | 3.59% | 3.85% | 4.13% | 4.38% | 5.33% | 5.57% | 6.12% | 6.78% | 9.32% |
| HC (g) | ECO | 1.77 | 1.82 | 1.86 | 1.90 | 1.95 | 2.49 | 2.55 | 2.62 | 2.71 | 2.82 |
| | TT | 1.99 | 2.06 | 2.13 | 2.21 | 2.28 | 2.94 | 3.04 | 3.18 | 3.37 | 3.55 |
| | Rel. Diff | 11.1% | 11.9% | 12.8% | 13.7% | 14.6% | 15.3% | 16.2% | 17.7% | 19.4% | 20.7% |
| CO (g) | ECO | 44.59 | 45.80 | 46.86 | 47.98 | 49.00 | 65.56 | 66.94 | 68.66 | 71.01 | 73.68 |
| | TT | 50.52 | 52.34 | 54.22 | 56.12 | 58.02 | 77.25 | 79.84 | 83.31 | 88.02 | 92.39 |
| | Rel. Diff | 11.7% | 12.5% | 13.6% | 14.5% | 15.6% | 15.1% | 16.2% | 17.6% | 19.3% | 20.2% |
| $NO_x$ (g) | ECO | 1.54 | 1.54 | 1.55 | 1.55 | 1.55 | 2.01 | 2.02 | 2.03 | 2.06 | 2.08 |
| | TT | 1.66 | 1.67 | 1.68 | 1.69 | 1.71 | 2.20 | 2.22 | 2.25 | 2.29 | 2.33 |
| | Rel. Diff | 7.2% | 7.6% | 8.0% | 8.5% | 8.9% | 8.6% | 8.9% | 9.5% | 10.2% | 10.8% |
| $CO_2$ (g) | ECO | 1184 | 1188 | 1194 | 1202 | 1209 | 1377 | 1386 | 1396 | 1412 | 1431 |
| | TT | 1220 | 1226 | 1235 | 1245 | 1255 | 1443 | 1455 | 1472 | 1497 | 1561 |
| | Rel. Diff | 2.9% | 3.1% | 3.3% | 3.5% | 3.7% | 4.6% | 4.7% | 5.2% | 5.7% | 8.3% |

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# Eco-Drive Systems

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# Eco-Cruise Control

## Overview

- Objective:
  - Develop a predictive fuel-optimum control system
- Input:
  - Desired speed and speed bounds (min/max speed)
- Building blocks:
  - Powertrain and fuel consumption model

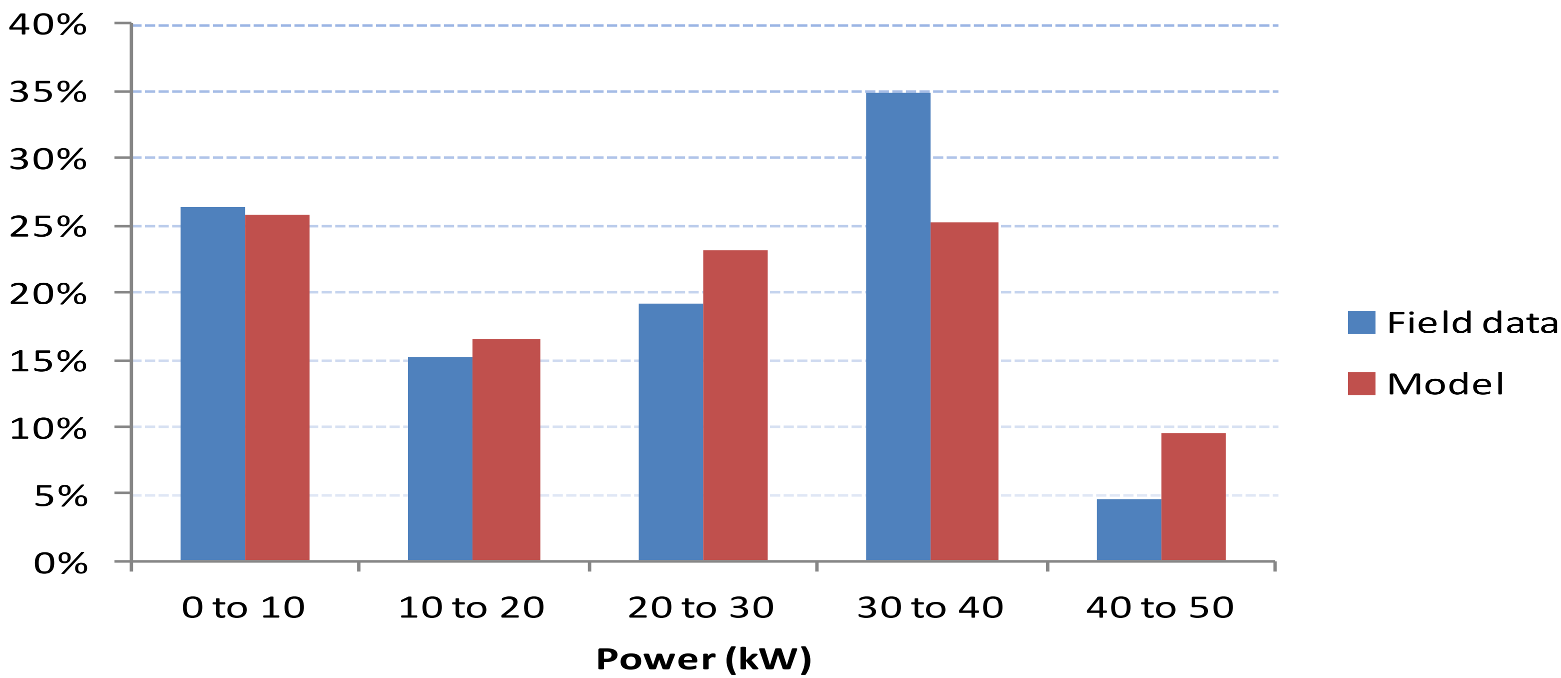

Rakha H., Ahn K.; Faris W., Moran, K. (2012), "Simple Vehicle Powertrain Model for Modeling Intelligent Vehicle Applications," *IEEE Transactions on Intelligent Transportation Systems*, Vol. 13(2), June 2012, ISSN 1524-9050, pp. 770-780.

Rakha, H., Ahn, K., Moran, K., Saerens, B., and Van den Bulck, E. (2011), "Virginia Tech Comprehensive Power-based Fuel Consumption Model: Model Development and Testing," *Transportation Research Part D: Transport and Environment*. doi:10.1016/j.trd.2011.05.008.

# Eco-Cruise Control

## Powertrain Model

- 2007 Chevy Malibu: I-81 southbound
  - 65 mph cruise control operation
  - Measured: 13,297 kW vs. Estimated: 13,871 kW (4.3% Error)



# Eco-Cruise Control

## VT-CPFM Model

- Virginia Tech Comprehensive Power-based Fuel consumption Model (VT-CPFM)

$$FC(t) = \begin{cases} a_0 + a_1 P(t) + a_2 P(t)^2 & \forall P(t) \geq 0 \\ a_0 & \forall P(t) < 0 \end{cases}$$

  - Has the ability to produce a control system that does not result in bang-bang control and
  - Is easily calibrated using publicly available data without the need to gather detailed engine and fuel consumption data.
  - Estimates $CO_2$ emissions ($R^2$=95%)

**Where**:
$\alpha_0$, $\alpha_1$, $\alpha_2$ are model constants that require calibration,
*P(t)* is the instantaneous total power in kilowatts (kW) at instant *t*, and
*w(t)* is the engine speed at instant *t*.

# Eco-Cruise Control

## Publications

Park S., Rakha H., Ahn K., Moran K., Saerens B., and Van den Bulck E., (2012), "Predictive Eco-cruise Control System: Model Logic and Preliminary Testing," *Transportation Research Record: Journal of the Transportation Research Board*, No. 2270, pp. 113-123, DOI: 10.3141/2270-14.

Saerens, B., Rakha, H., Ahn, K., and Van den Bulck, E. (2013), "Assessment of Alternative Polynomial Fuel Consumption Models for use in ITS Applications," *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations*, DOI:10.1080/15472450.2013.764801.

Saerens B., Rakha H., Diehl M., Van den Bulck E. (2013), "Eco-Cruise Control for Passenger Vehicles: Methodology," *Transportation Research Part D: Transport and Environment*, Vol. 19, pp. 20-27.

Park S., Rakha H., Ahn K., and Moran K. (2013), "Fuel Economy Impacts of Manual, Conventional Cruise Control, and Predictive Eco-Cruise Control Driving," *International Journal of Transportation Science and Technology*, Vol. 2, no. 3, pp. 227-242.

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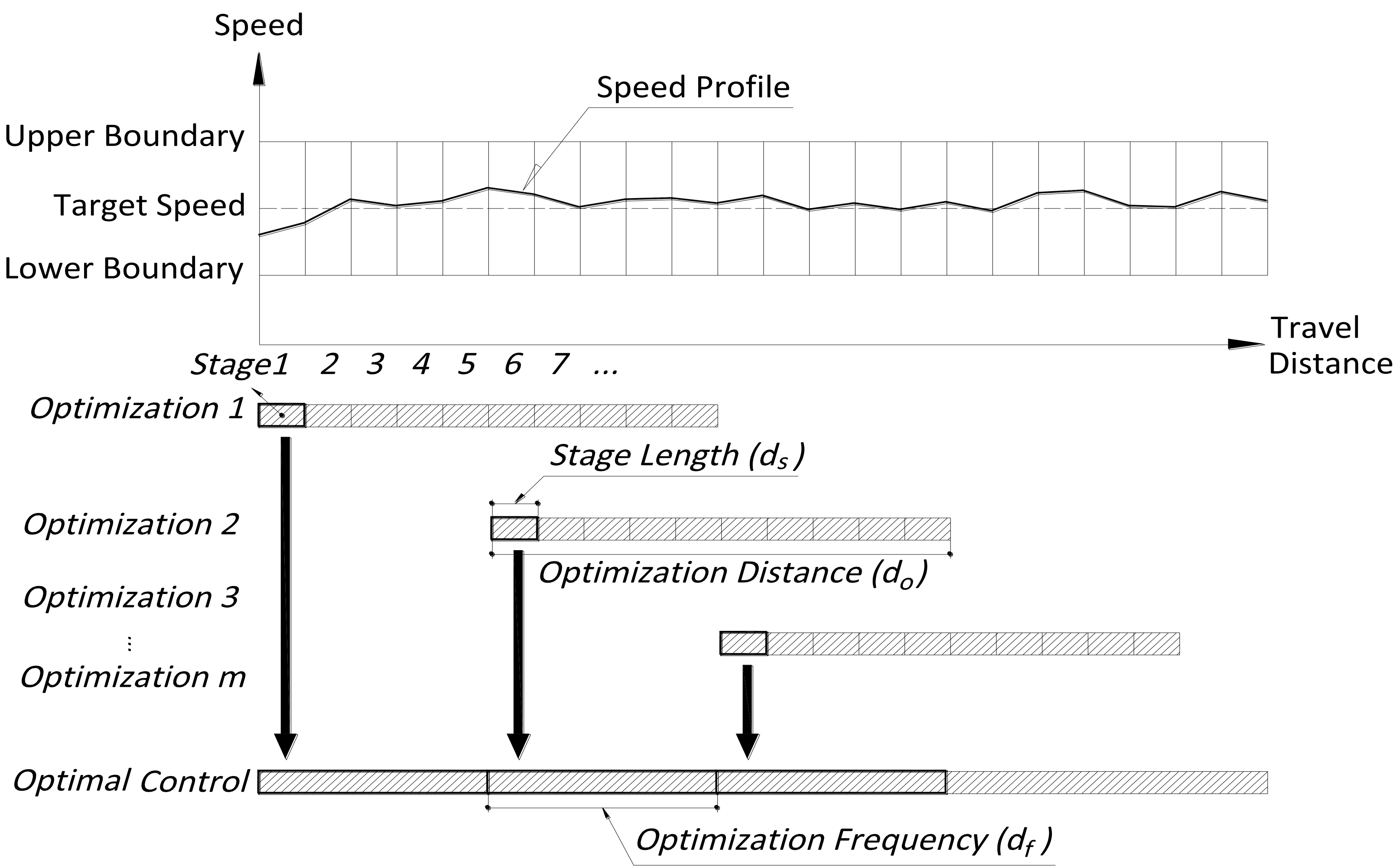
# Eco-Cruise Control

## Model Logic



# Eco-Cruise Control

## Model Logic

- Three step optimization:
  - Prune search space using powertrain model
    - Speed and gear space that the vehicle is physically able to achieve for the given topography and vehicle characteristics
  - Discretize continuous search space
    - Use speed and gear levels to construct a graph
  - Compute optimum control (minimum path)
    - The vehicle speed and gear changes over each stage considering a cost function at stage transitions

$$Cost = w_1 \times FC_{(v_0, v_1)} + w_2 \times \left| \frac{v_1}{v_{ref}} - 1 \right| \times FC_{(v_{ref})} + w_3 \times \left| g_1 - g_0 \right| \times FC_{(v_{ref})}$$

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# Eco-Cruise Control

## Model Testing (NYC to LA)

- 2790 miles with mostly highway sections
  - Use I-80, I-76, I-70, I-15, and I-10 route
- Assumed no interaction with other vehicles

# Eco-Cruise Control

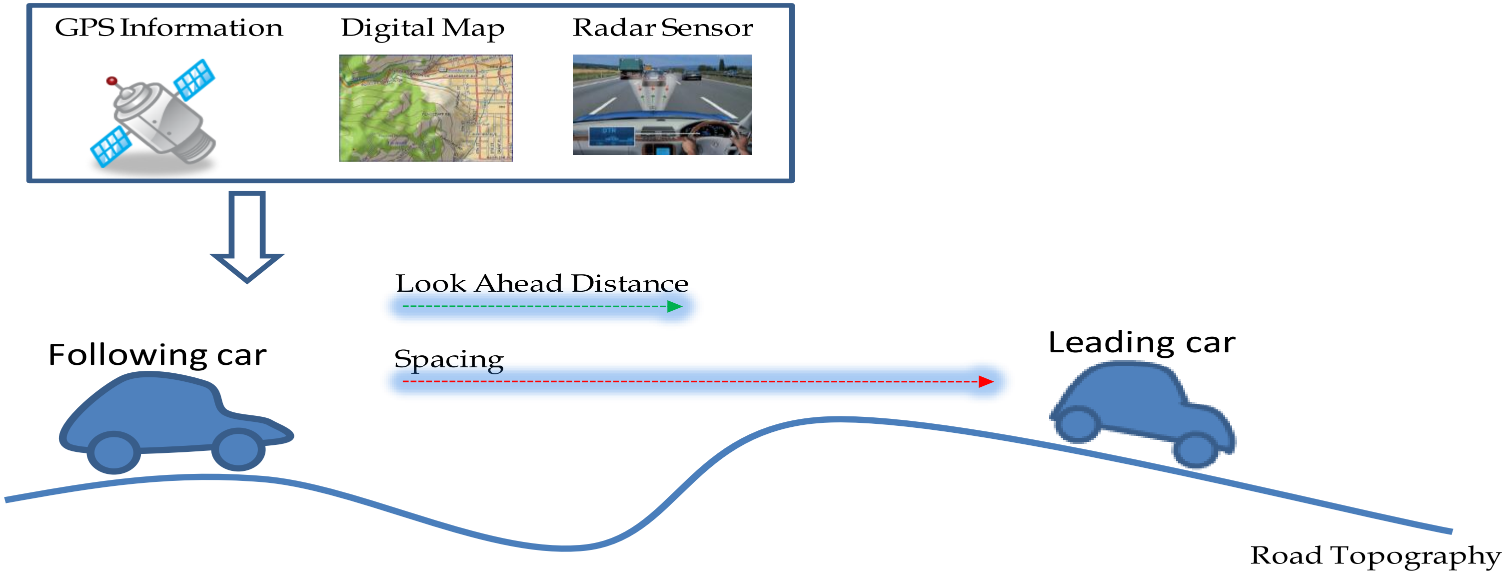
## Model Testing (NYC to LA)

| Toyota Camry | Fuel (L) | MPG | Fuel Saving | TT (hr) | Avg. Spd (mph) | $\sigma_s$ (mph) | $\Delta$TT (%) |
|---|---|---|---|---|---|---|---|
| Conventional | 252.8 | 41.9 | | 43.0 | 64.9 | 0.7 | |
| Predictive (+5 &-1 mph) | 239.6 | 44.3 | 5.2% | 43.3 | 64.4 | 1.2 | 0.8% |
| Conventional (Spd : 60.7mph) | 239.2 | 44.3 | 5.4% | 45.1 | 60.6 | 0.6 | 4.8% |
| Predictive (± 5 mph) | 227.2 | 46.7 | 10.1% | 46.0 | 60.7 | 2.0 | 7.0% |

| Chevy Tahoe | Fuel (L) | MPG | Fuel Saving | TT (hr) | Avg. Spd (mph) | $\sigma_s$ (mph) | $\Delta$TT (%) |
|---|---|---|---|---|---|---|---|
| Conventional | 469.3 | 22.6 | | 42.9 | 65.0 | 0.9 | |
| Predictive (+5 &-1 mph) | 423.7 | 25.0 | 9.7% | 43.5 | 64.1 | 0.7 | 1.4% |
| Conventional (Spd: 60.3mph) | 431.4 | 24.6 | 8.1% | 45.9 | 60.8 | 1.0 | 6.9% |
| Predictive (± 5 mph) | 387.1 | 27.4 | 17.5% | 46.3 | 60.3 | 1.2 | 7.9% |

# Eco-Drive System
## Model Overview

- Predictive Eco-Cruise Control (ECC) and car-following




Ahn K., Rakha H., and Park S. (2013), "ECO-Drive Application: Algorithmic Development and Preliminary Testing," *Transportation Research Record: Journal of the Transportation Research Board*, No. 2341, Vol. 2, pp. 1-11.

# Eco-Cooperative Adaptive Cruise Control in the Vicinity of Signalized Intersections

Kamalanathsharma R. and Rakha H. (In press), “Leveraging Connected Vehicle Technology and Telematics to Enhance Vehicle Fuel Efficiency in the Vicinity of Signalized Intersections,” *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations*.

Kamalanathsharma R. and Rakha H. (2014), "Fuel-Optimal Vehicle Throttle Control: Model Logic and Preliminary Testing,” Presented at the 93rd Transportation Research Board Annual Meeting, Washington DC, January 12-16, CD-ROM [Paper # 14-0433].

Kamalanathsharma R. and Rakha H. (2014), Agent-Based Simulation of Eco-Speed Controlled Vehicles at Signalized Intersections," Presented at the 93rd Transportation Research Board Annual Meeting, Washington DC, January 12-16, CD-ROM [Paper # 14-1028].

Kamalanathsharma R., Rakha H., and (2014), "Simulation Testing of Connected Vehicle Applications in a Cloud-based Traffic Simulation Environment," Presented at the 93rd Transportation Research Board Annual Meeting, Washington DC, January 12-16, CD-ROM [Paper # 14-4260].

# ECACC

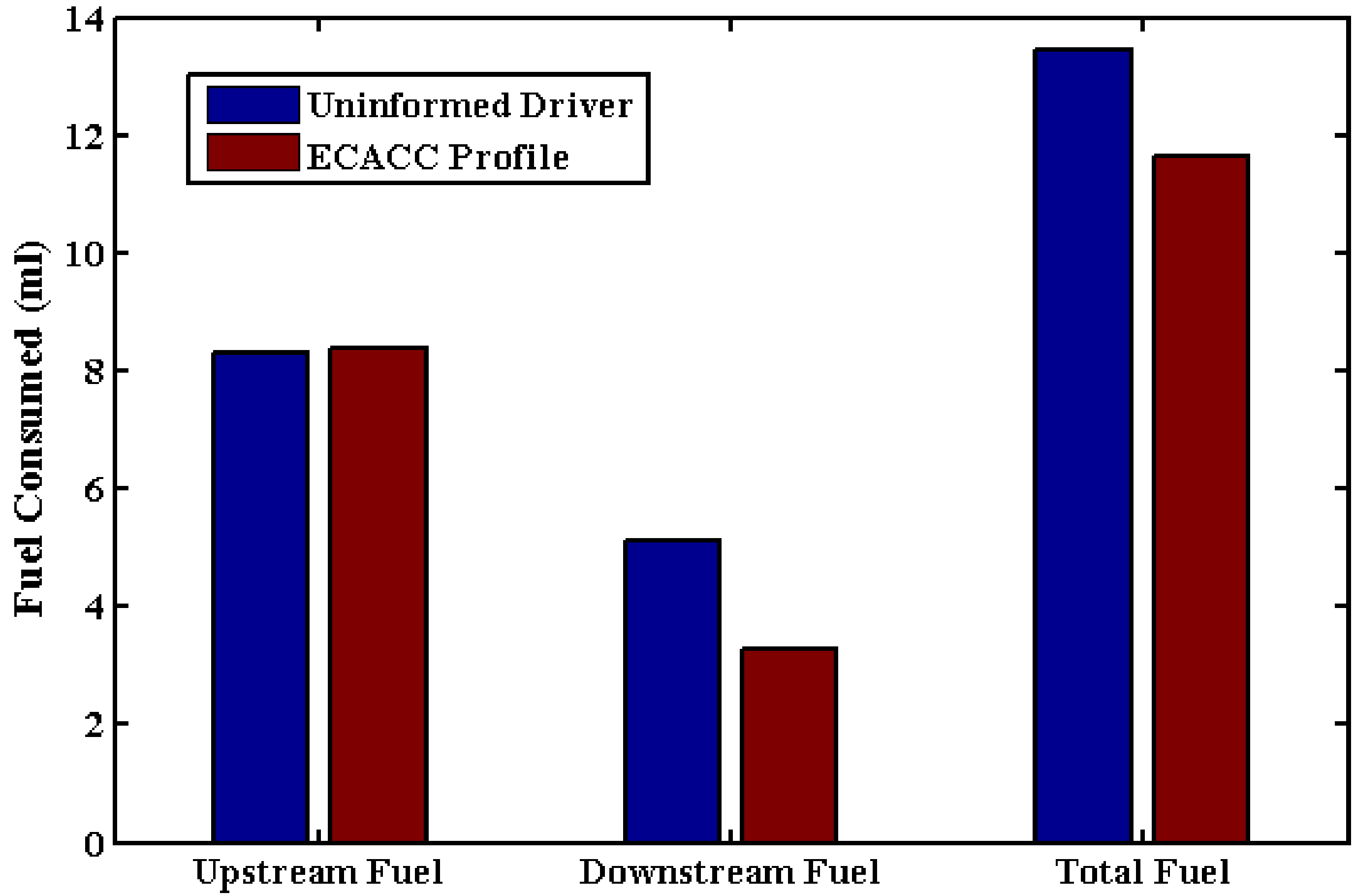
## Formulation

- Problem solved using DP
  - Initial state: When SPaT information is received.
  - Intermediate state: When vehicle should reach stop line.
  - Final state: Location when vehicle reaches its desired speed for lowest acceleration level.
- Use A* algorithm to speed computation of minimum path

$$\min J_u + J_d$$

Where: $J_u = \int_{t_0}^{t_s} FC(t)dt \quad J_d = \int_{t_s}^{t_f} FC(t)dt$

# ECACC
## Results



# Intersection Cooperative Adaptive Cruise Control System


Zohdy I. and Rakha H. (2012), "Agent-Based Framework for Modeling Driver Left-Turn Gap Acceptance Behavior at Signalized Intersections," *Transportation Research Record: Journal of the Transportation Research Board*, No. 2316, pp. 1-10.

Zohdy I. and Rakha H. (In press), "Enhancing Roundabout Operations via Vehicle Connectivity," *Transportation Research Record: Journal of the Transportation Research Board*.

Zohdy I. and Rakha H. (In press), "Intersection Management via Vehicle Connectivity: The iCACC System Concept," *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations*.

Zohdy I. and Rakha H. (2012), "Moving Horizon Optimization Algorithm for Cooperative Adaptive Cruise Control Systems at Intersections," First European Symposium on Quantitative Methods in Transportation Systems, Lausanne, Switzerland, September 4-7, 2012.

Zohdy I., Kamalanathsharma R., and Rakha H., (2012), "Intersection Management for Autonomous Vehicles using iCACC," 15th IEEE Intelligent Transportation Systems Conference, Alaska, USA; September 16-19, 2012.

Zohdy I. and Rakha H., (2012), "Game Theory Algorithm for Intersection-based Cooperative Adaptive Cruise Control (CACC) Systems," 15th IEEE Intelligent Transportation Systems Conference, Alaska, USA; September 16-19, 2012.

Zohdy I. and Rakha H. (2012), "Optimizing Driverless Vehicles at Intersections," ITS World Congress, Vienna, Austria, Oct. 22-26. (Session TS108 - Autonomous vehicle concepts - Friday 11:00 - 12:30).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# iCACC

## Formulation

**Objective:** Total Delay Minimization

$$Min: \sum_{i=1}^{\Omega^1} D_i$$

**Subject to:**

(1) Ensure that the FIFO rule is applied to all vehicles in the same lane;

$$(OT_i + D_i) - (OT_j + D_j) \ge H_{\min}(l_{im}, l_{jm});$$

(2) The arrival of two intersecting vehicles at the same conflict point is separated by a minimum safe time gap;

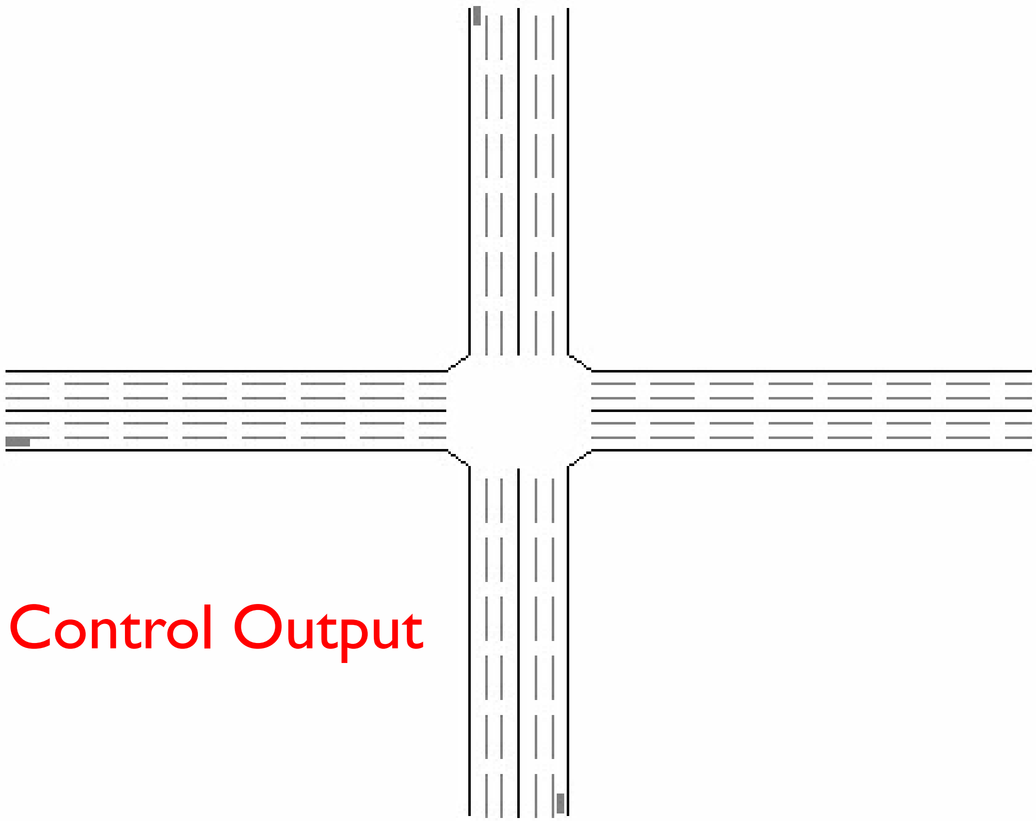
$$\left|(OT_i + D_i + \tau_{mn}) - (OT_k + D_k + \tau_{nm})\right| \ge \Delta t(l_{im}, l_{kn}, c_{mn});$$

(3) The arrival time of each vehicle at the conflict point is greater than any arrival time computed in the previous simulation step

$$(OT_i + D_i + \tau_{mn}) \ge \max\left[(OT_i + D_i + \tau_{mn}), (OT_p + D_p + \tau_{nm})\right];$$

# iCACC

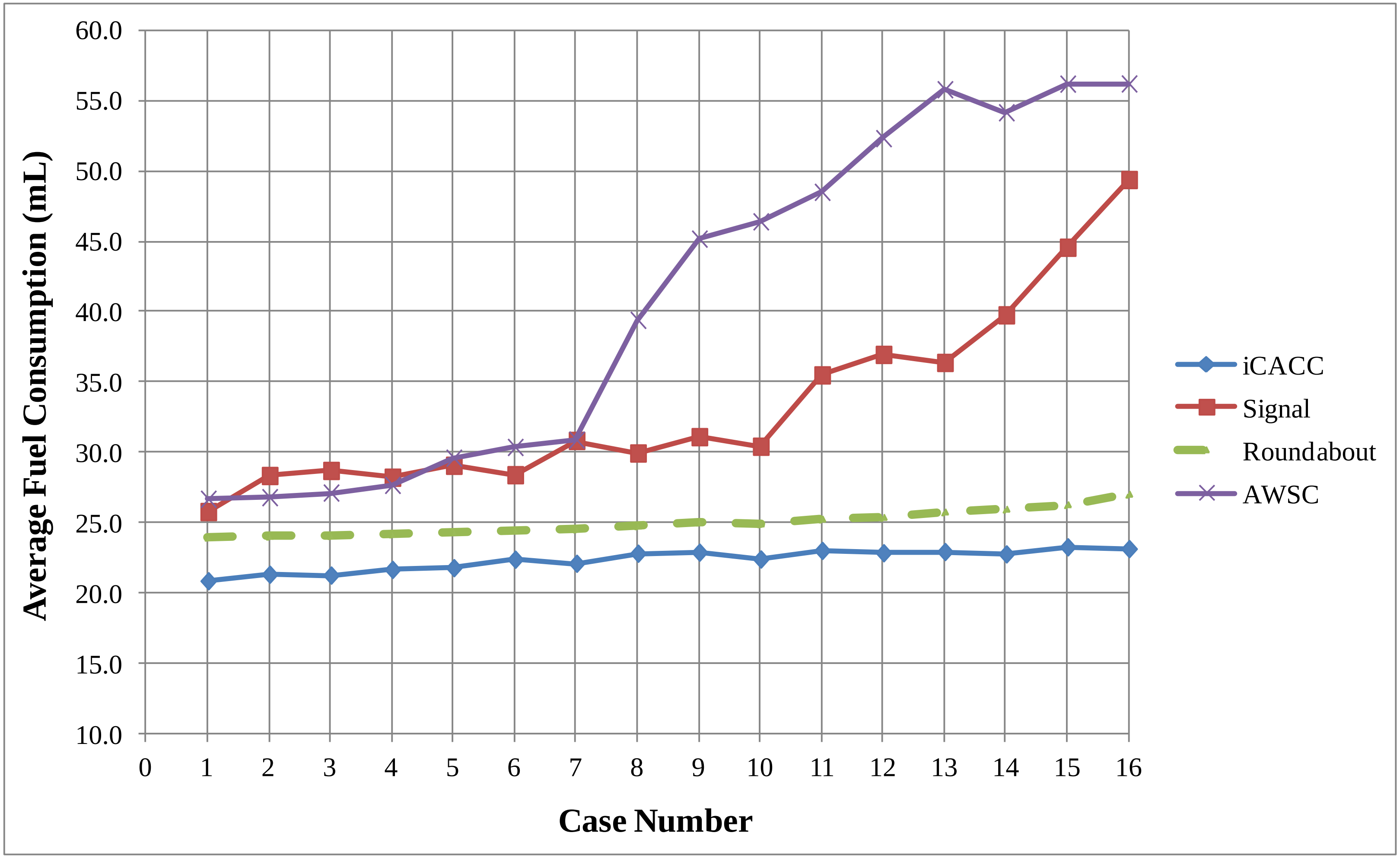
## Example Demonstration



Sample Control Output

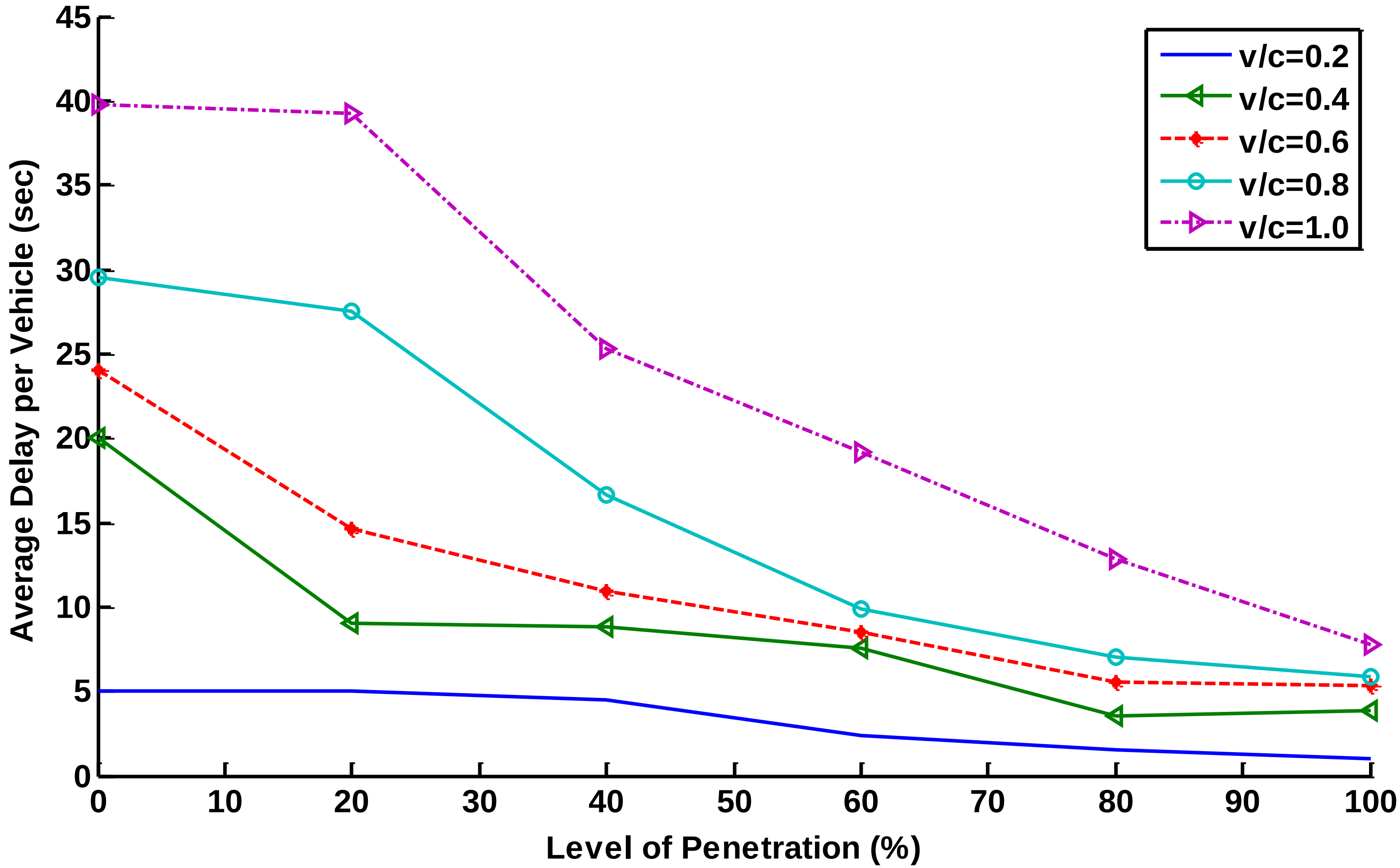
# iCACC

## System Evaluation



# iCACC

## Roundabout System Enhancement

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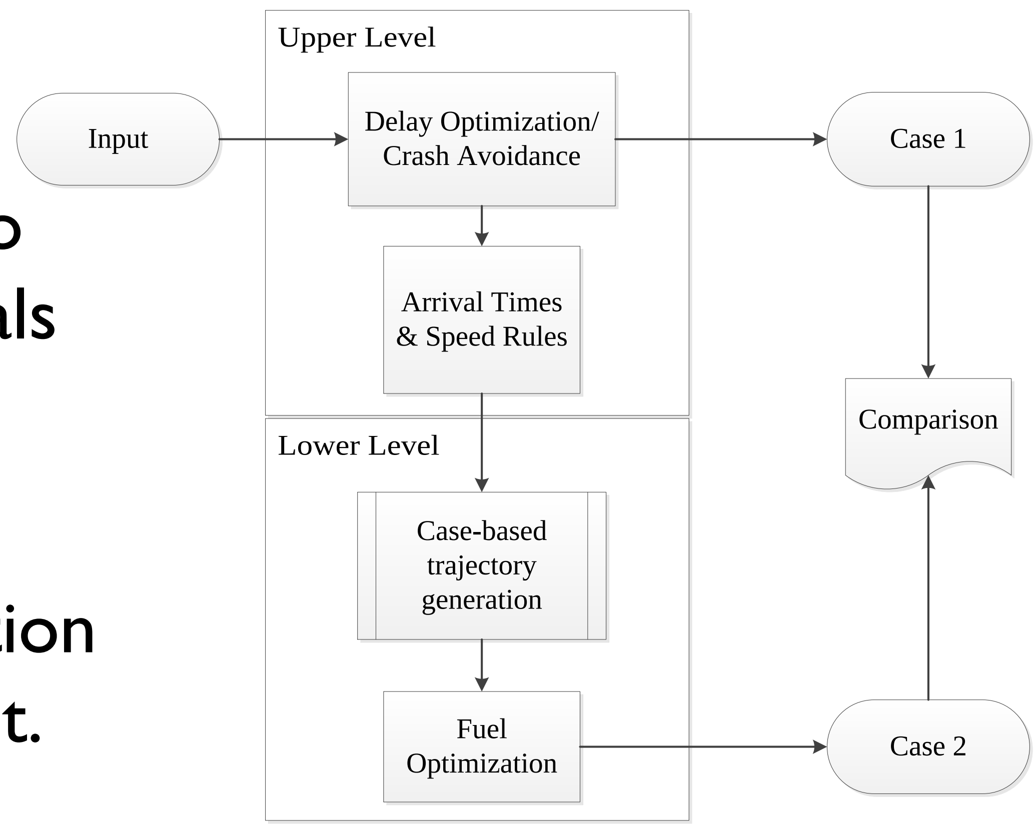
# iCACC

## Bi-level Optimization

- Upper level
  - Delay optimization to schedule arrivals of vehicles
- Lower level
  - Fuel consumption optimization s.t. upper level constraints



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# On-going and Future Work

- Eco-traffic signal control:
  - Designing of traffic signal timings to reduce vehicle fuel consumption levels
  - Field testing a prototype system
- Real-time eco-scheduling and routing of buses
- Developing a prototype in-vehicle eco-routing system
- Integrating speed harmonization algorithms with eco-drive systems