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Driving Transportation with Technology

Developing and Testing Eco-Drive Systems

Dr. Hesham Rakha, Dr. Kyoungho Ahn & Dr. Sangjun Park

Center for Sustainable Mobility
Virginia Tech Transportation Institute (VTTI), Blacksburg, VA

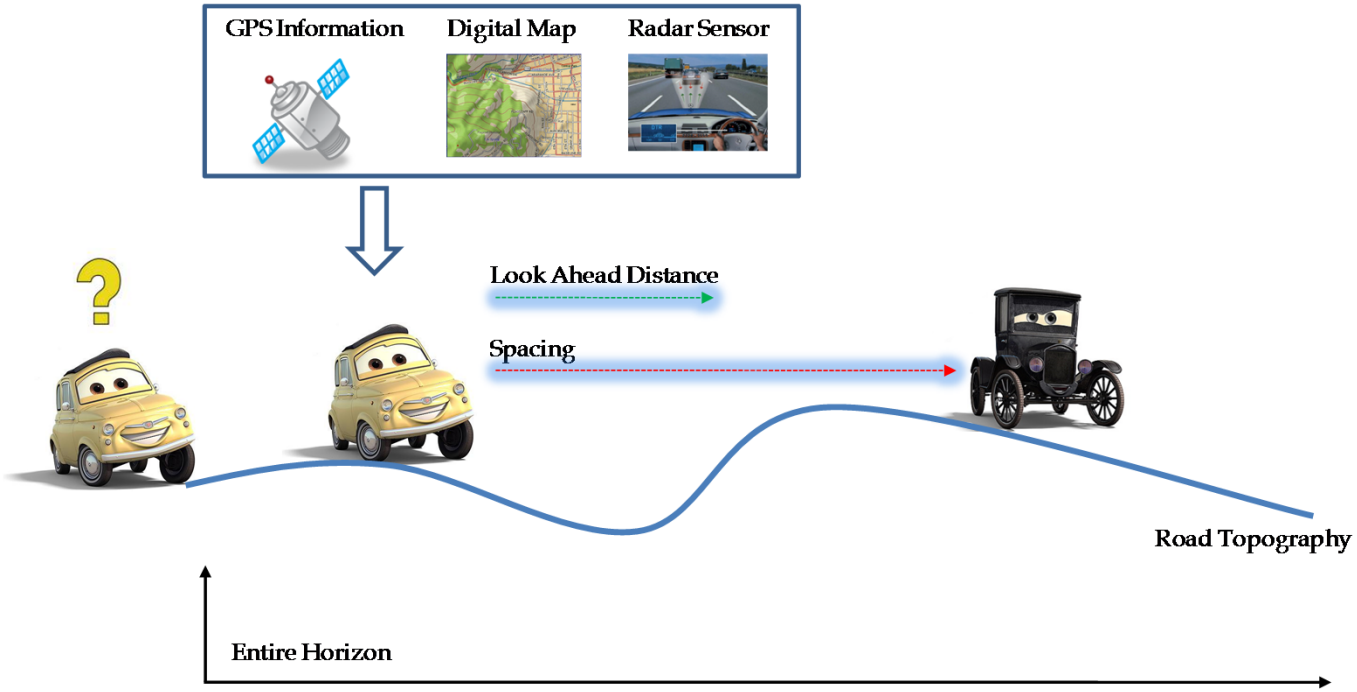
E-mail: hrakha@vt.edu. Phone: +1-540-231-1505

What is Eco-Driving and its Impacts?

- A way of driving that reduces fuel consumption and greenhouse gas emissions – Ecodriving.org
- Teaching eco-driving can improve actual fuel efficiency by an average of 17 percent - McKinsey & Company 2009
- 1% of the highway trip is responsible for 16, 19, 4, 3, and 4% of the trip's total HC, CO, NO_X, CO_2, and fuel consumption – Ahn and Rakha 2008

Objectives

- Develop an Eco-drive system
  - Predictive Eco-Cruise Control (ECC) system
  - Eco-car-following



Presentation Overview

- Describe the building blocks of the Eco-drive system
  - Fuel Consumption Model
  - Powertrain Model
  - Predictive Eco-Cruise Model
  - Car-Following Model
- Overview of proposed algorithm
- Simulation results
- Study conclusions and recommendations

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Fuel Consumption Modeling

Fuel Consumption Models

VT-CPFM

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

$$FC(t) = \begin{matrix} \alpha_0 + \alpha_1 P(t) + \alpha_2 P(t)^2 & \forall\, P(t) \geq 0 \\ \alpha_0 & \forall\, P(t) < 0 \end{matrix}$$

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

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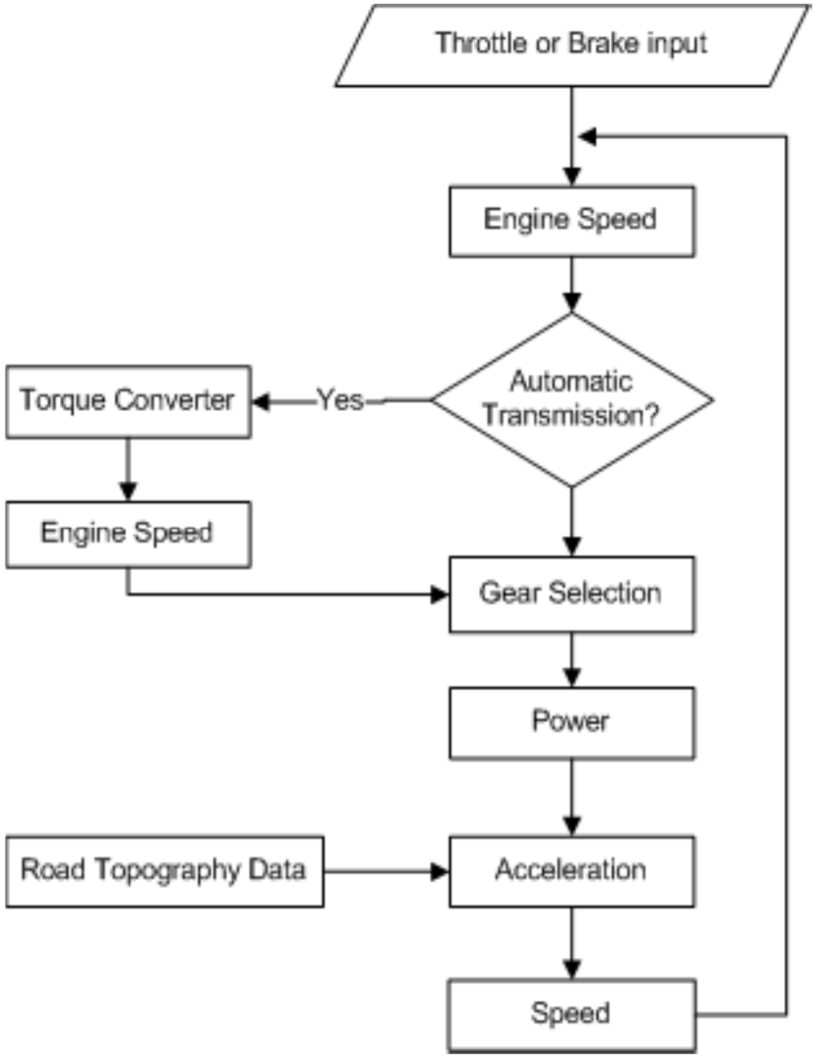
Vehicle Powertrain Modeling

Vehicle Powertrain Model

- Typical powertrain models:
  - Computationally intensive
    - Challenging to integrate within microscopic traffic simulation software
  - Require proprietary parameters
    - Require gathering field data for the entire envelope of operation of a vehicle.
- Simple vehicle powertrain model needed:
  - CSM developed a model used within the context of this approach

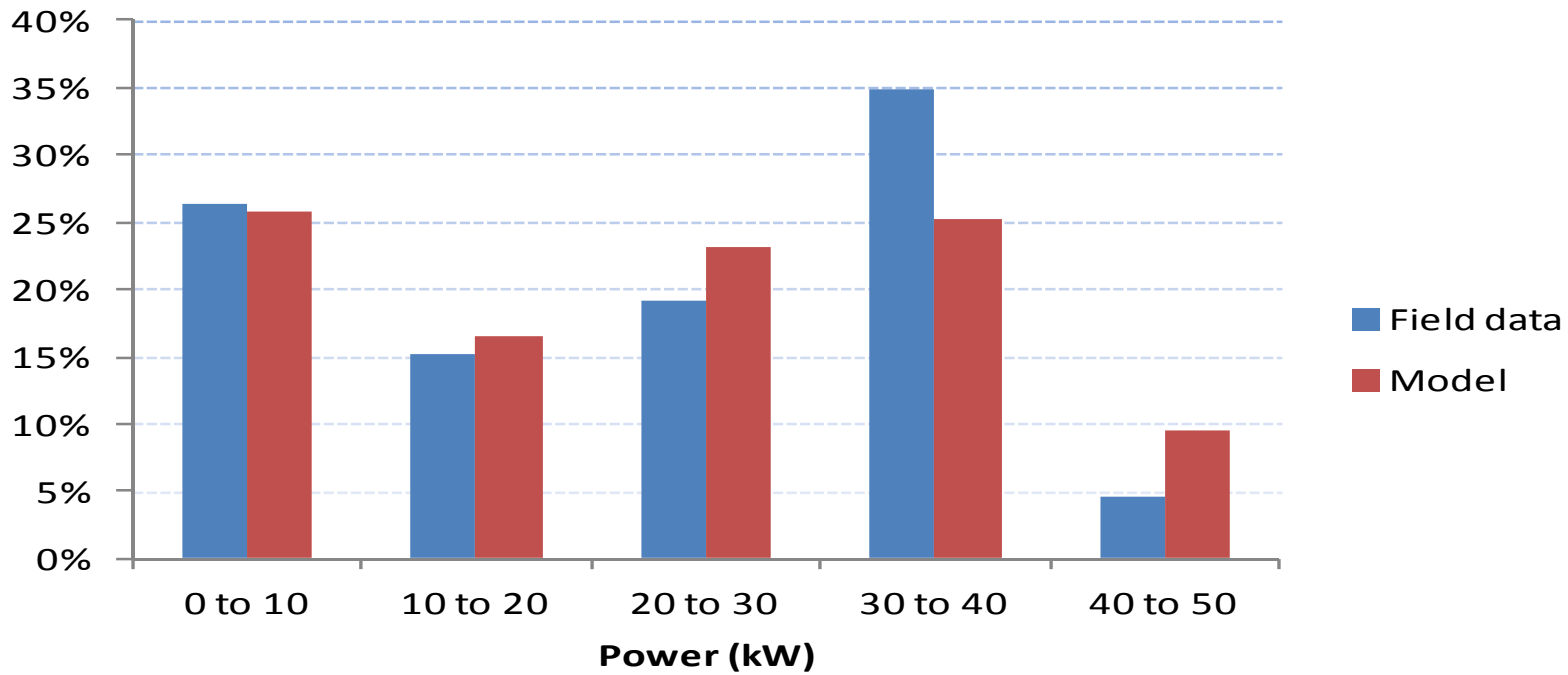
Vehicle Powertrain Model

- The proposed model
  - Uses driver throttle input to compute the engine speed and power and finally compute the vehicle acceleration, speed, and position
  - Can be calibrated using vehicle parameters that are publically available without the need for field data collection.



Vehicle 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)



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Predictive Eco-Cruise Model

Predictive Eco-Cruise Model

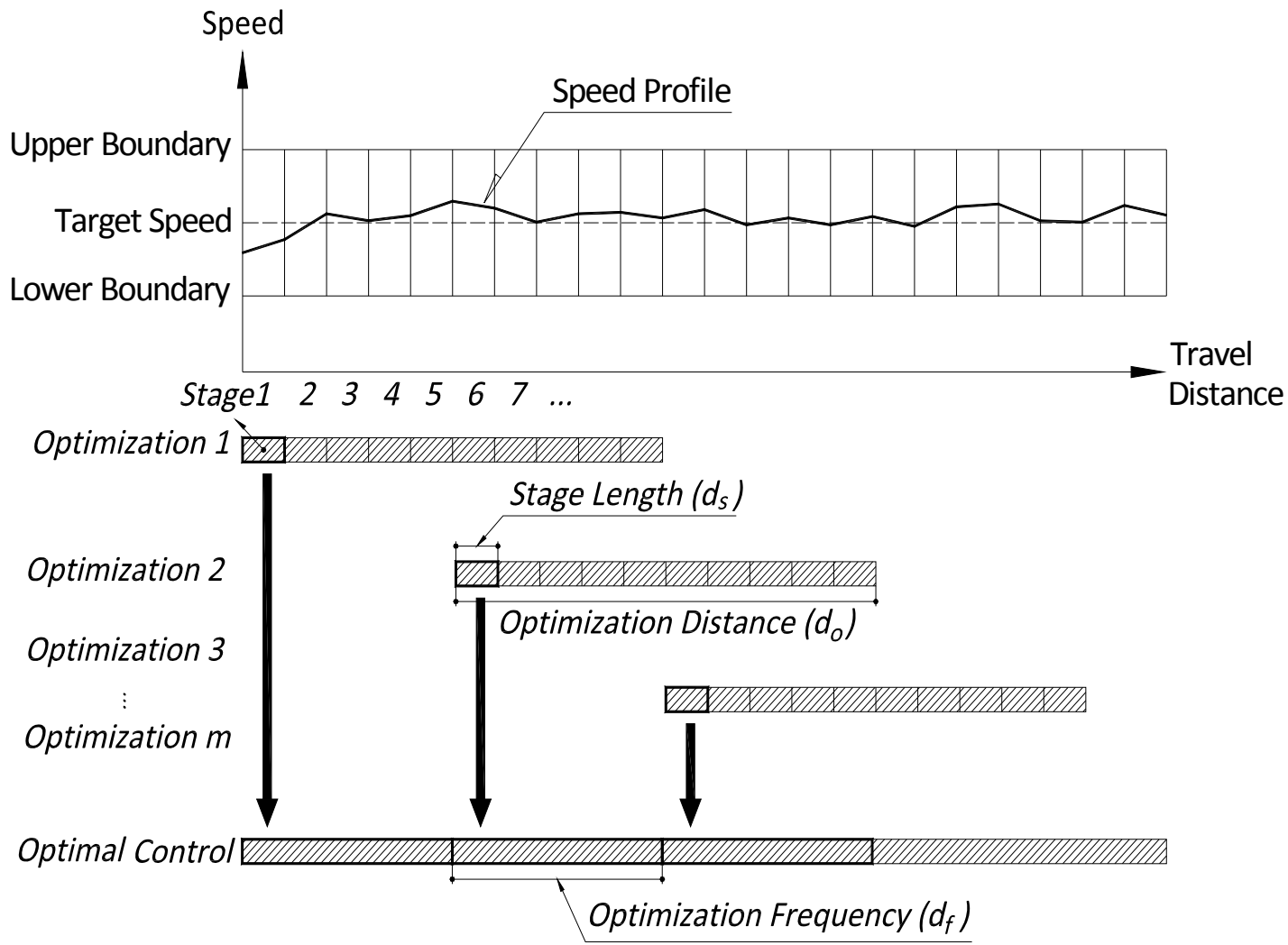
- The proposed predictive eco-cruise control system
  - Generates optimal vehicle controls using topographic data.
  - Optimizes the vehicle controls in advance using a dynamic programming (DP) implementation of Dijkstra's shortest path algorithm.
  - Requires three system parameters:
    - Discretization distance (or stage length), the look-ahead distance, and the optimization frequency.

Predictive Eco-Cruise Model

- Three step optimization:
  - Define 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

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

Predictive Eco-Cruise Model



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Car-Following Model

Car-Following Model

- Car-following models define relationships between a following and preceding vehicle in a range of inter-vehicle spacing.
- Modeled as
  - Equations of motion under steady-state conditions plus
  - Constraints that govern the behavior of vehicles while moving from one steady-state to another.
- The Rakha-Pasumarthy-Adjerid (RPA) model is used
  - Van Aerde steady-state car-following model
  - Vehicle dynamics acceleration and deceleration constraints

Car-Following Model

- Steady-State Modeling

$$\tilde{s}_n(t+\Delta t) = c_1 + c_3 u_n(t+\Delta t) + \frac{c_2}{u_f - u_n(t+\Delta t)}$$

$$u_n(t+\Delta t) = \frac{-c_1 + c_3 u_f + \tilde{s}_n(t+\Delta t) - \sqrt{A}}{2c_3}$$

$$A = \left(c_1 - c_3 u_f - \tilde{s}_n(t+\Delta t)\right)^2 - 4c_3\left(\tilde{s}_n(t+\Delta t)u_f - c_1 u_f - c_2\right)$$

where $s_n(t)$ is vehicle spacing at time t, $u_n(t)$ is speed of vehicle n at time t (km/h), u_f is free-flow speed (km/h), Δt is length of time interval, c_1 is fixed vehicle spacing constant (km), c_2 is first variable vehicle spacing constant (km^2/h), and c_3 is second variable vehicle spacing constant (h).

Car-Following Model

- Collision Avoidance Modeling

$$s_n(t) = \frac{1}{k_j} + \frac{u_n(t+\Delta t)^2 - u_{n-1}(t+\Delta t)^2}{25920\mu f_b \eta_b g}$$

$$u_n(t+\Delta t) = \sqrt{u_{n-1}(t+\Delta t)^2 + 25920\mu f_b \eta_b g\left(s_n(t) - \frac{1}{k_j}\right)}$$

Where k_j is jam density (veh/km) and $u_{n-1}(t)$ is speed of vehicle n-1 at time t (km/h). This deceleration level is assumed to be equal to $\mu f_b \eta_b g$, where μ is the coefficient of roadway friction, f_b is the driver brake pedal input [0,1], η_b is the brake efficiency [0,1], and g is the gravitational acceleration (9.8067 m/s^2).

Car-Following Model

- Vehicle Acceleration Modeling
  - Vehicle acceleration is governed by vehicle dynamics
  - Vehicle dynamics models compute the maximum vehicle acceleration levels from the resultant forces acting on a vehicle.

$$u_n(t+\Delta t) = u_n(t) + 3.6\frac{F_n(t) - R_n(t)}{m_n}\Delta t$$

$$F_n(t) = \min\left(3600 f_p \beta \eta_d \frac{P_n}{u_n(t)}, m'_n\, g\mu\right)$$

$$R_n(t) = \frac{\rho}{25.92} C_d C_h A_f u_n(t)^2 + m_n g \frac{c_{r0}}{1000}\left(c_{r1} u_n(t) + c_{r2}\right) + m_n g G(t)$$

where $F_n(t)$ is vehicle tractive force (N), $R_n(t)$ is total resistance force (N), m_n is vehicle mass (kg),fp is the driver throttle input [0,1], β is the gear reduction factor (unitless), η_d is the driveline efficiency (unitless), P_n is the vehicle power (kW), m'_n is the mass of vehicle n on its tractive axle (kg), g is the gravitational acceleration (9.8067 m/s^2), μ is the coefficient of friction (unitless), ρ is the air density at sea level (1.2256 kg/m^3), C_d is the vehicle drag coefficient (unitless), C_h is the altitude correction factor (unitless), A_f is the vehicle frontal area (m^2), c_{r0} is the rolling resistance constant (unitless), c_{r1} is the rolling resistance constant (h/km), c_{r2} is the rolling resistance constant (unitless), and $G(t)$ is the roadway grade at instant t (unitless).

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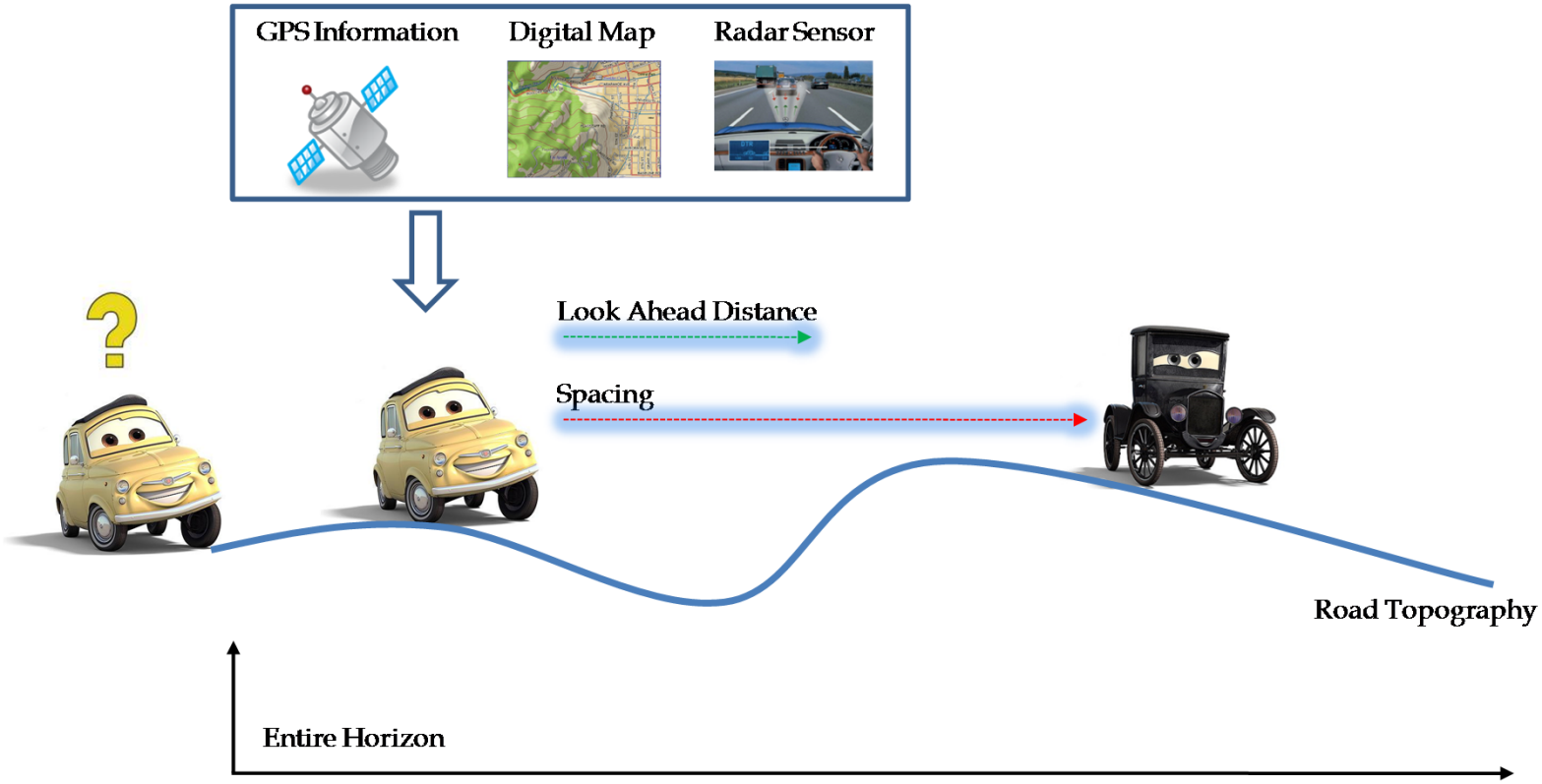
Proposed Algorithm

Proposed Algorithm



Proposed Algorithm

- Step 1: If the spacing between the subject and lead vehicle is beyond the car-following threshold proceed to step 3, otherwise proceed with step 2.
- Step 2: Estimate the vehicle at instant $t+\Delta t$ using the RPA car-following model and proceed to step 4.
- Step 3: Using DP, the optimum vehicle speed trajectory over the look-ahead distance (d_o) is estimated considering a spatial discretization of length d_s (stage length).
- Step 4: Move the vehicle and then go back to step 1 at the conclusion of the time step Δt; otherwise end the simulation at $t=T$.

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Simulation Results

Key Input Variables

- Car-following spacing threshold
- Car-following model parameters
  - Free-flow speed, Jam density, Speed-at-capacity, and capacity
- Vehicle data
  - Powertrain related data, fuel economy data
- Roadway topography
- Real-time GPS data
- Lead vehicle location data (or spacing data)

Simulation Overview

- Three Test Vehicles
  - 2011 Toyota Camry (22/33 mpg)
  - 2008 Chevy Tahoe (14/20 mpg), and
  - 2008 Chevy Malibu Hybrid (24/32 mpg)
- Tested Two Lead Vehicle Trajectories (14miles)
  - I-81 SB Field Data (2007 Malibu Manual Driving)
  - I-81 SB Eco-Driving Speed Profile (2011 Camry)
- Tested different car-following parameters
  - Car-following threshold: 100m, 50m, and 30m
  - Throttle level: 100%, 60%, and 40%
  - Fixed vs. dynamic threshold

Summary Results – I-81 Speed Profile

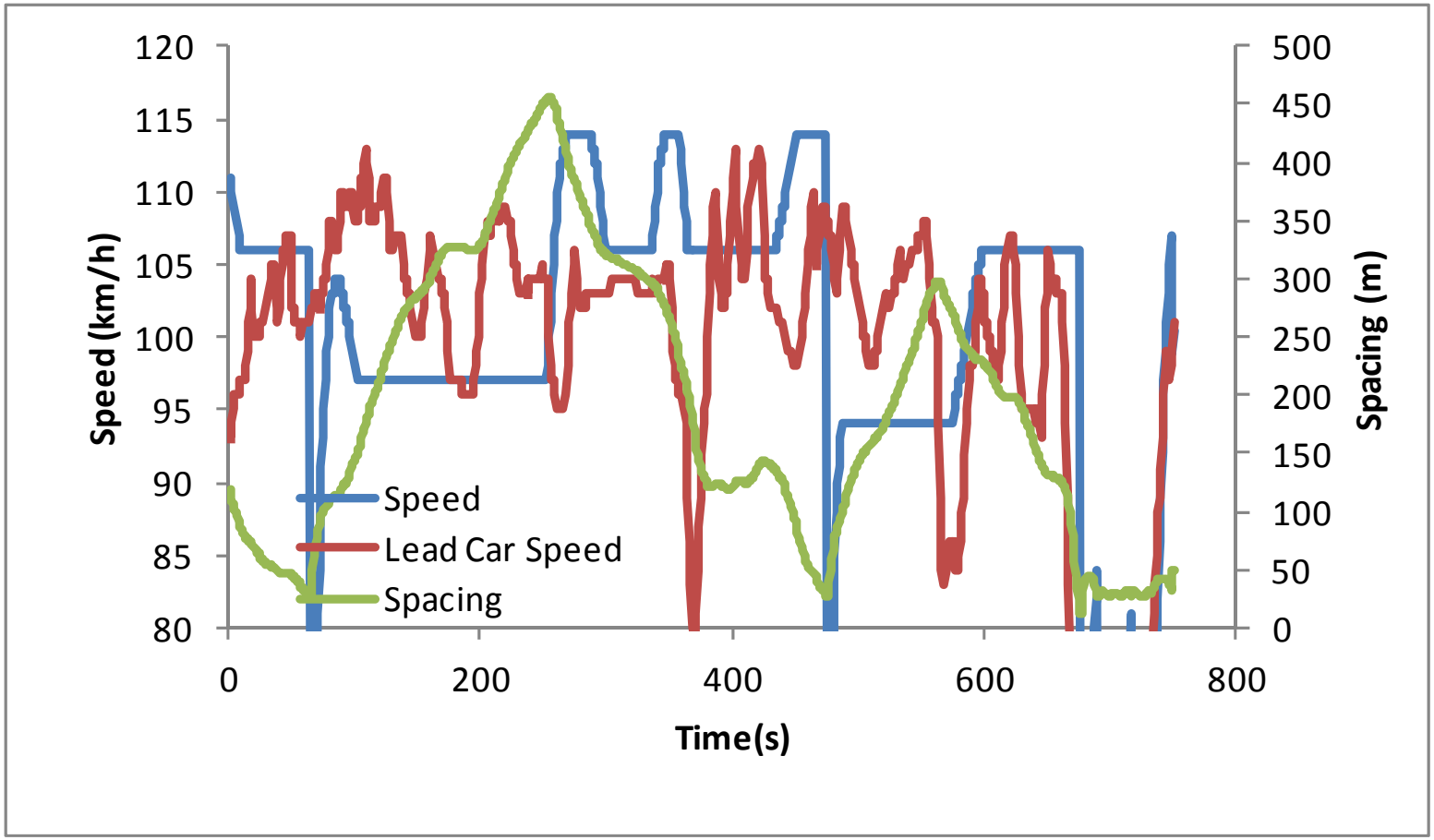
	2011 Camry	2008 Tahoe	2008 Malibu Hybrid
Car-following	13.5 mpg	8.9 mpg	16.2 mpg
Eco-cruise	24.6 mpg (82%)	14.3 mpg (60%)	25.4 mpg (57%)
Eco-Cruise (100m following threshold)	13.5 mpg (-0.6%)	8.7 mpg (-2%)	16.1 mpg (-0.1%)
Eco-Cruise (50m following threshold)	16.0 mpg (18%)	9.6 mpg (8%)	19.2 mpg (19%)
Eco-Cruise (30m following threshold)	20.5 mpg (51%)	10.8 mpg (21%)	21.2 mpg (31%)

Summary Results – I-81 Speed Profile
2011 Toyota Camry

	100% Throttle	60% Throttle	40% Throttle
Car-following	13.5 mpg	15.8 mpg (16%)	20.2 mpg (49%)
Eco-cruise	24.6 mpg (82%)		
Eco-Cruise (100m following threshold)	13.5 mpg (-0.6%)	15.8 mpg (16%)	20.2 mpg (49%)
Eco-Cruise (50m following threshold)	16.0 mpg (18%)	18.6 mpg (38%)	20.3 mpg (50%)
Eco-Cruise (30m following threshold)	20.5 mpg (51%)	20.9 mpg (55%)	20.8 mpg (53%)

Summary Results – I-81 Speed Profile

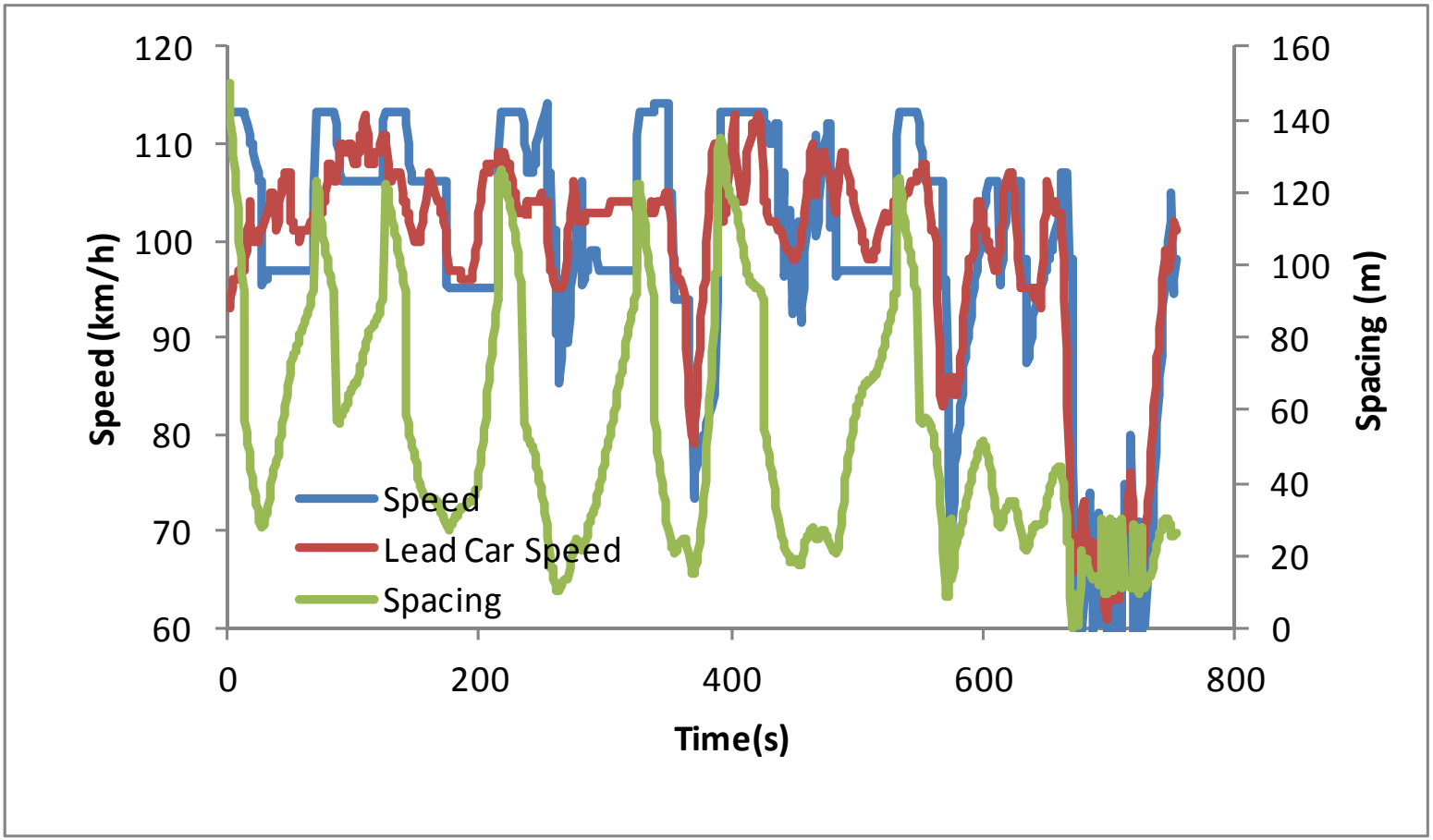
Car-following Threshold of 30m



- 20.5 mpg, average spacing=196m, maximum spacing= 457m

Summary Results – I-81 Speed Profile

Car-following Threshold 30m & Max Spacing 100m



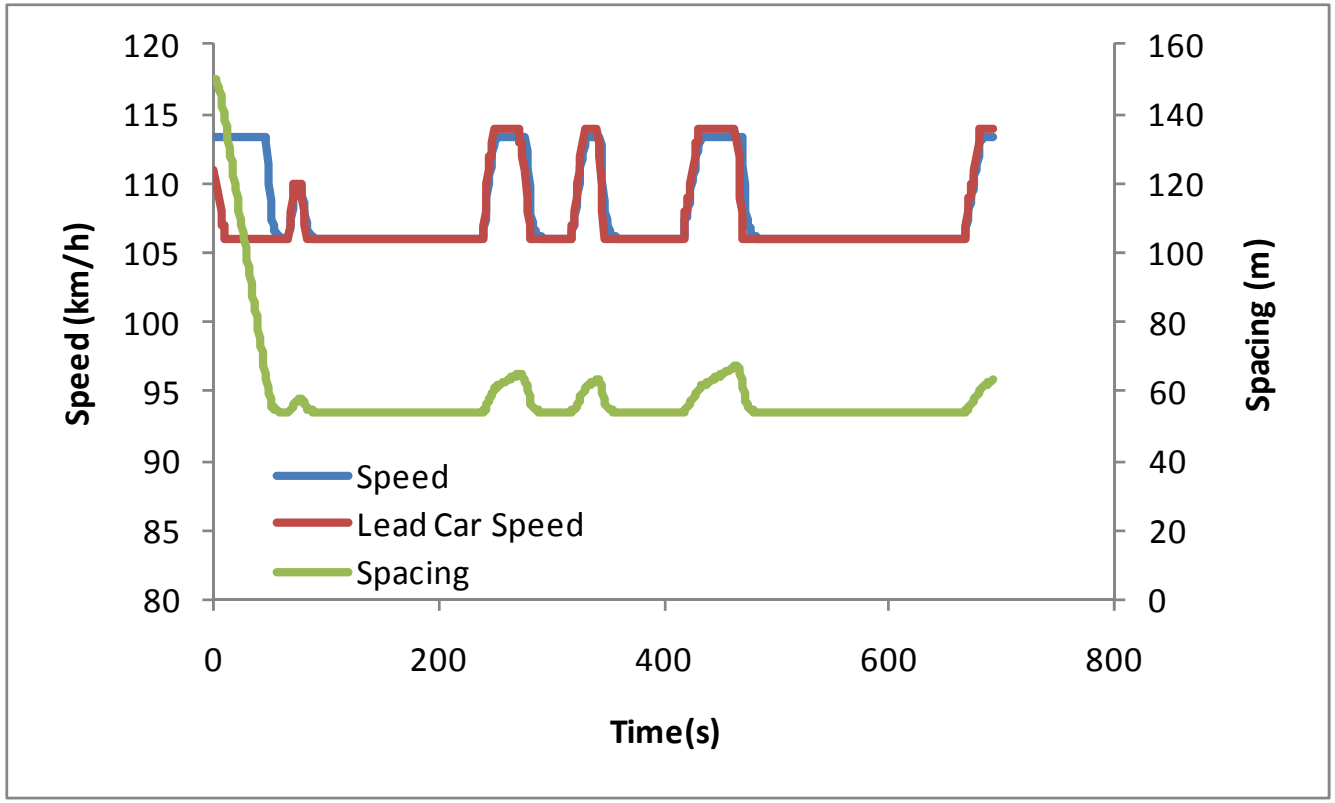
- If Spacing > max. spacing (100m) then use car-following model
- 17.2 mpg, average spacing = 48m, maximum spacing = 133m

Summary Results – I-81 Speed Profile
2011 Toyota Camry

	Fixed Car-following Threshold	Dynamic Car-following Threshold	Dynamic Car-following Threshold with Max Spacing Limit
Eco-cruise	24.6 mpg		
Eco-Cruise (100m following threshold)	13.5 mpg (50m, 60m)		
Eco-Cruise (50m following threshold)	16.0 mpg (78m, 161m)	15.8 mpg (54m, 179m)	15.9 mpg (53m, 183m)
Eco-Cruise (30m following threshold)	20.5 mpg (196m, 457m)	18.3 mpg (80m, 289m)	17.2 mpg (48m, 133m)

- Fuel economy, average and maximum vehicle spacing

Following ECC Vehicle



- Car-following only - 23.7 mpg
- ECC mode – 24.6 mpg

Conclusions and Recommendations

- Study shows that the proposed system can save fuel significantly consumption maintaining reasonable vehicle spacing
  - Toyota Camry: 27% fuel saving and average spacing: 48m along I-81
- Vehicle operations at lower power demands significantly enhance vehicle fuel economy (up to 49%)
  - Not as significant as the use of the ECC (improved fuel economy up to 82%).
- ECC equipped vehicles benefit following vehicles
  - Following vehicles will benefit by just following the lead vehicle.
- There is a need to quantify the potential benefits of using the proposed system at a network-wide level.

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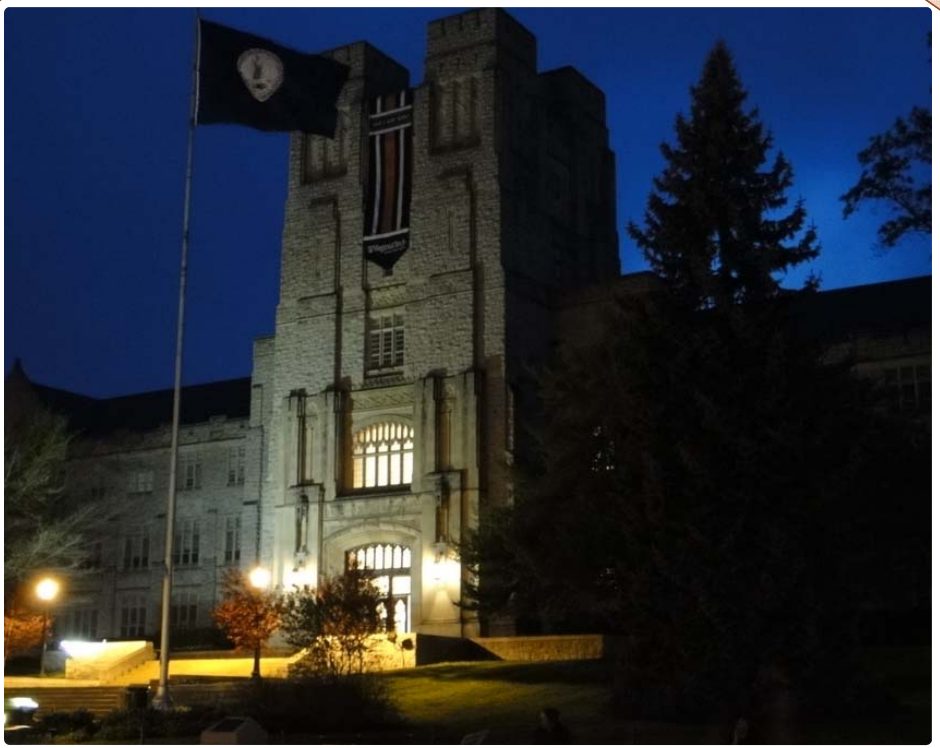

Go Hokies!

Thank You!