Eco-Vehicle Speed Control at Signalized Intersections using I2V Communication

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Overview

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- Model Description
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Introduction

- The research develops an eco-speed control system to reduce vehicle fuel consumption in the vicinity of signalized intersections.

I2V
Uses I2V communication to receive SPaT information at an upcoming traffic signal.

SPaT
Using available SPaT and queued vehicle information optimize the vehicle trajectory.

Vehicle Trajectory
Using state-of-the-art vehicle fuel consumption and acceleration models, fuel consumption of vehicle trajectories are compared.

Display
Vehicle-speed is assumed to be force-followed.

Alternately, instantaneous velocity advisory can be displayed to the driver.

Similar Research

Author	Findings	Shortcomings
Barth et al. [3]	• Studied TSS to drivers using CMS and in-vehicle devices. • Found 40% savings	• Used TTR info to advise drivers not to slow down if red is near.
Asadi & Vahidi [4]	• Developed a cruise control which reduces Pr(reach stop-bar @ red). • Showed 47% savings.	• Alternate speed profiles not studied using fuel consumption models.
Tielert et al. [5]	• Used VISSIM simulation to find factors affecting fuel savings if I2V communication is present	• Used PHEM model for comparison and not optimization.
Malakorn & Park [6]	• Studied a CACC based on I2V • min{length of dec & acc} & min{idling time}	• No FC model in objective. • Downstream neglected.
Mandava et al. [7]	• Optimal instantaneous velocity to drivers using TSS. • min{rate of dec/acc}	• No FC model in objective

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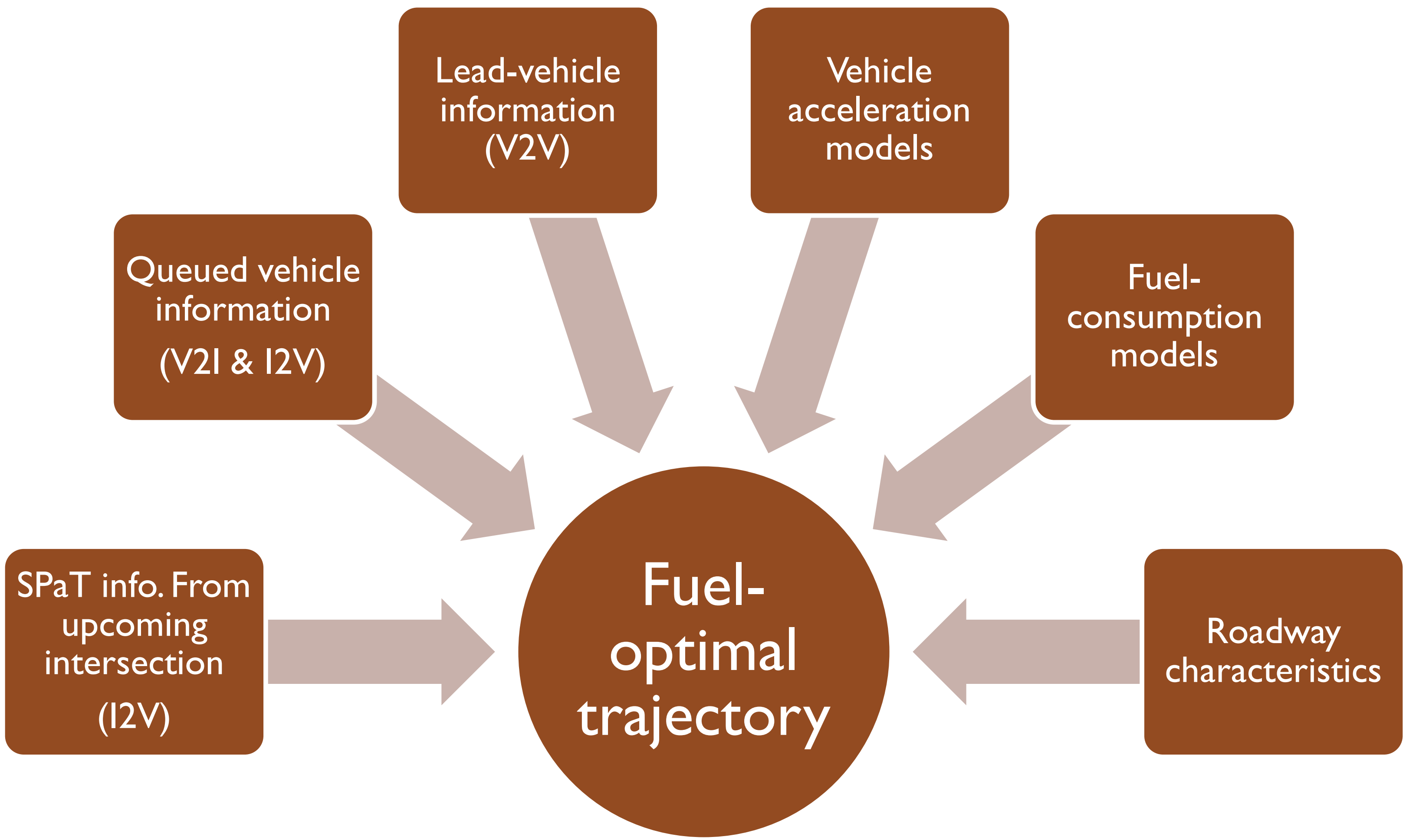
Model Description

- Previous publications used a simplified objective function.
- Here, the system computes a "proposed time to reach intersection" using
  - SPaT information
  - Queued vehicle information
  - Approaching vehicle information
- Computes a "proposed fuel-optimal trajectory" using
  - Vehicle deceleration and acceleration models
  - Microscopic fuel consumption models
  - Roadway characteristics

Model Description



Model Logic

- Signal is currently GREEN
  - Case 1: GREEN will continue so that vehicle can pass through at current speed.
  - Case 2: GREEN will end soon but vehicle can legally pass through intersection during the green or yellow indication if it speeds up within speed limit.
  - Case 3: GREEN will end soon and vehicle cannot pass during this phase.
- Signal is currently RED
  - Case 4: RED will continue but vehicle needs to be delayed to receive GREEN indication.
  - Case 5: RED will end soon so that vehicle will receive GREEN when it reaches stop-line at current speed.

Model Logic

- Cases 1,2, 3 and 5 are fairly simple
- Case 4 requires trajectory optimization every time step within detection zone.
- Min{fuel consumed}
- Subject to
  - Fixed travel distance upstream.
  - Fixed time to reach intersection.
  - Variable speed at intersection.
  - Vehicle acceleration characteristics downstream to accelerate back to initial speed.

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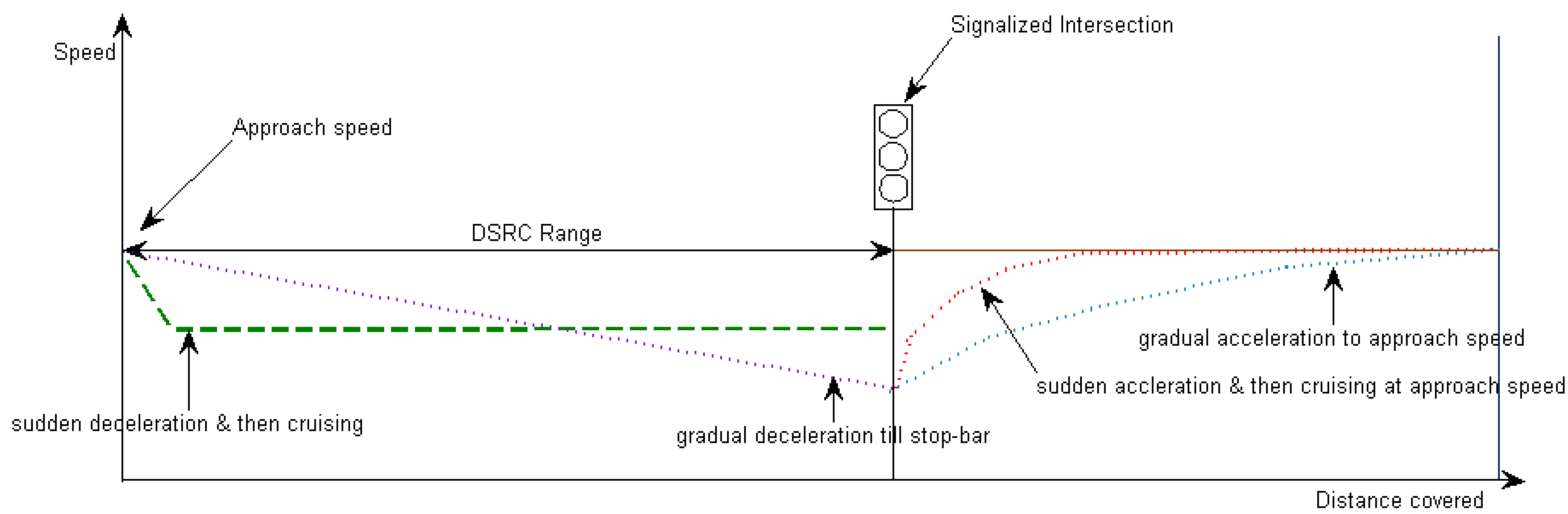
Model Logic

- Speed trajectory at intersection is divided into:
  - Upstream section (deceleration to achieve delay) &
  - Downstream section (accelerate to original speed)
  - Cruising section to maintain a constant distance of travel.



Technology

Deceleration Model

TTG = t seconds

DTI = x meters

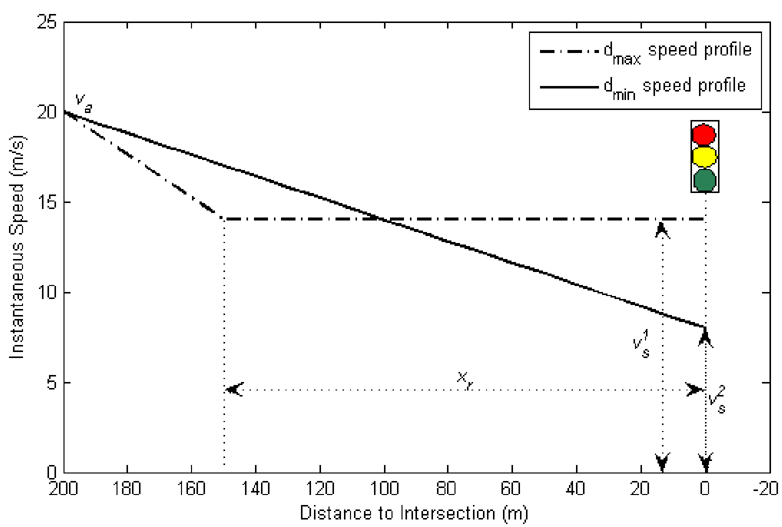
Approach speed = v_a m/s

Speed at signal = v_s m/s

Delay required = Δt seconds

Veh. deceleration = d m/s^2

Cruising dist. = x_r m



Conserve x and t :

$$x = \frac{v_a^2 - v_s^2}{2d} + x_r \quad \text{and} \quad t = \frac{v_a - v_s}{d} + \frac{x_r}{v_s}$$

Combining them:

$$t = \frac{v_a - v_s}{d} + \frac{1}{v_s}\left(x - \frac{v_a^2 - v_s^2}{2d}\right)$$

Solving for v_a :

$$v_s = v_a - d \cdot t + \sqrt{d\left(d \cdot t^2 - 2v_a t + 2x\right)}$$

For any v_a , x_r is given by:

$$x_r = x - \frac{v_a^2 - v_s^2}{2d}$$

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Acceleration Model

- Rakha & Lucic Model [8] was used.
  - Vehicle dynamics model.
  - Acceleration = Resultant Force/mass
  - Resultant Force = Tractive Force - Resistive Force

$$F = \min\left(3600\, f_p \beta \eta_d \frac{P}{v}, m_{ta} g \mu\right)$$

$$R = \frac{\rho}{25.92} C_d C_h A_f v^2 + mg \frac{c_{r0}}{1000}\left(c_{r1} v + c_{r2}\right) + mgG$$

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Fuel Consumption Model

- Virginia Tech Comprehensive Power-based Fuel Model (VT-CPFM) Type 1[2].
  - Based on instantaneous power

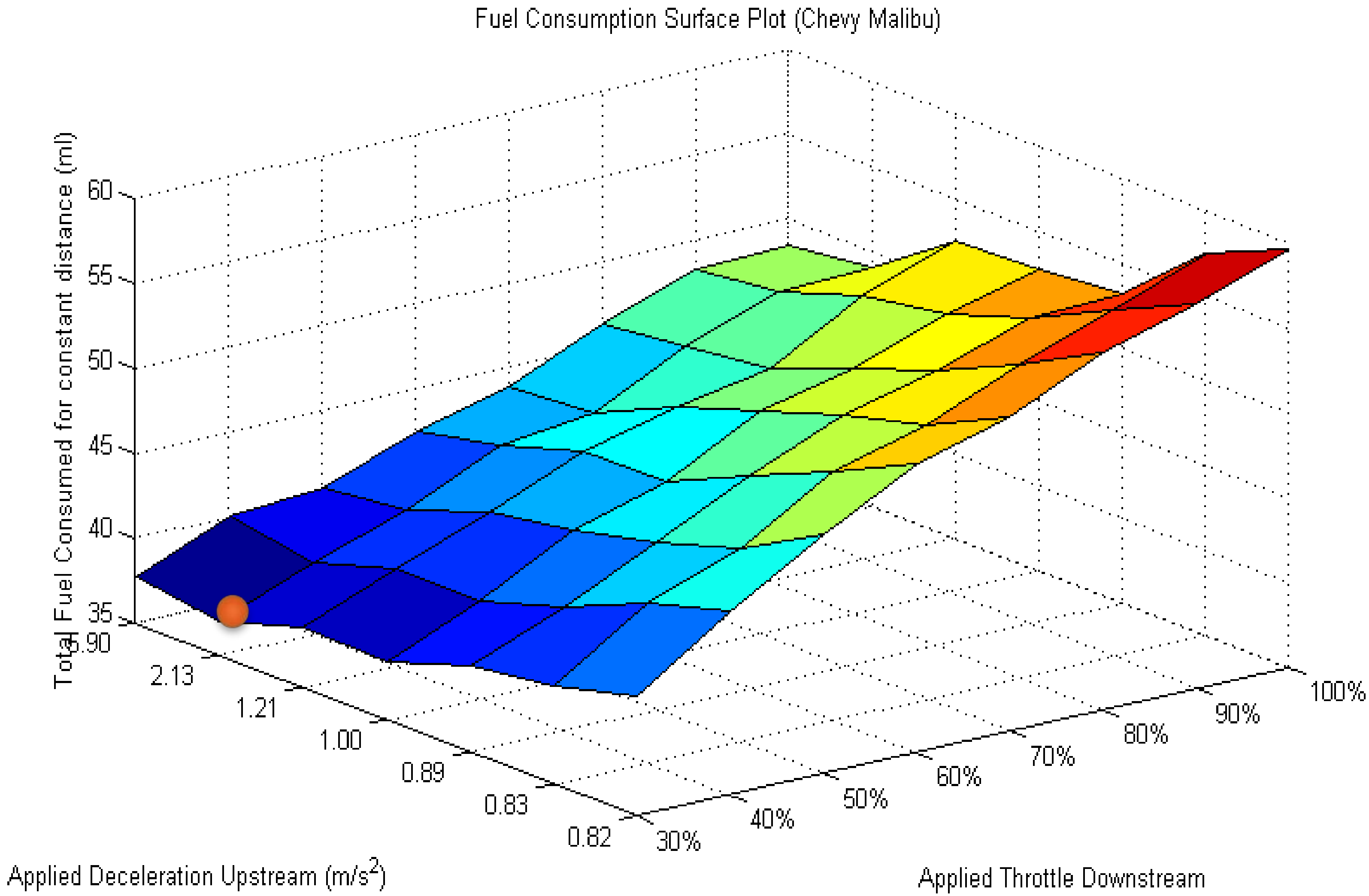
$$FC(t) = \begin{cases} \alpha_0 + \alpha_1 P(t) + \alpha_2 P(t)^2 & \forall\ P(t) \geq 0 \\ \alpha_0 & \forall\ P(t) < 0 \end{cases}$$

  - Parameters α_0, α_1 and α_2 can be calibrated using EPA fuel economy ratings.
  - Does not result in a bang-bang control
    - Optimum acceleration is not necessarily full throttle acceleration

Example Illustration

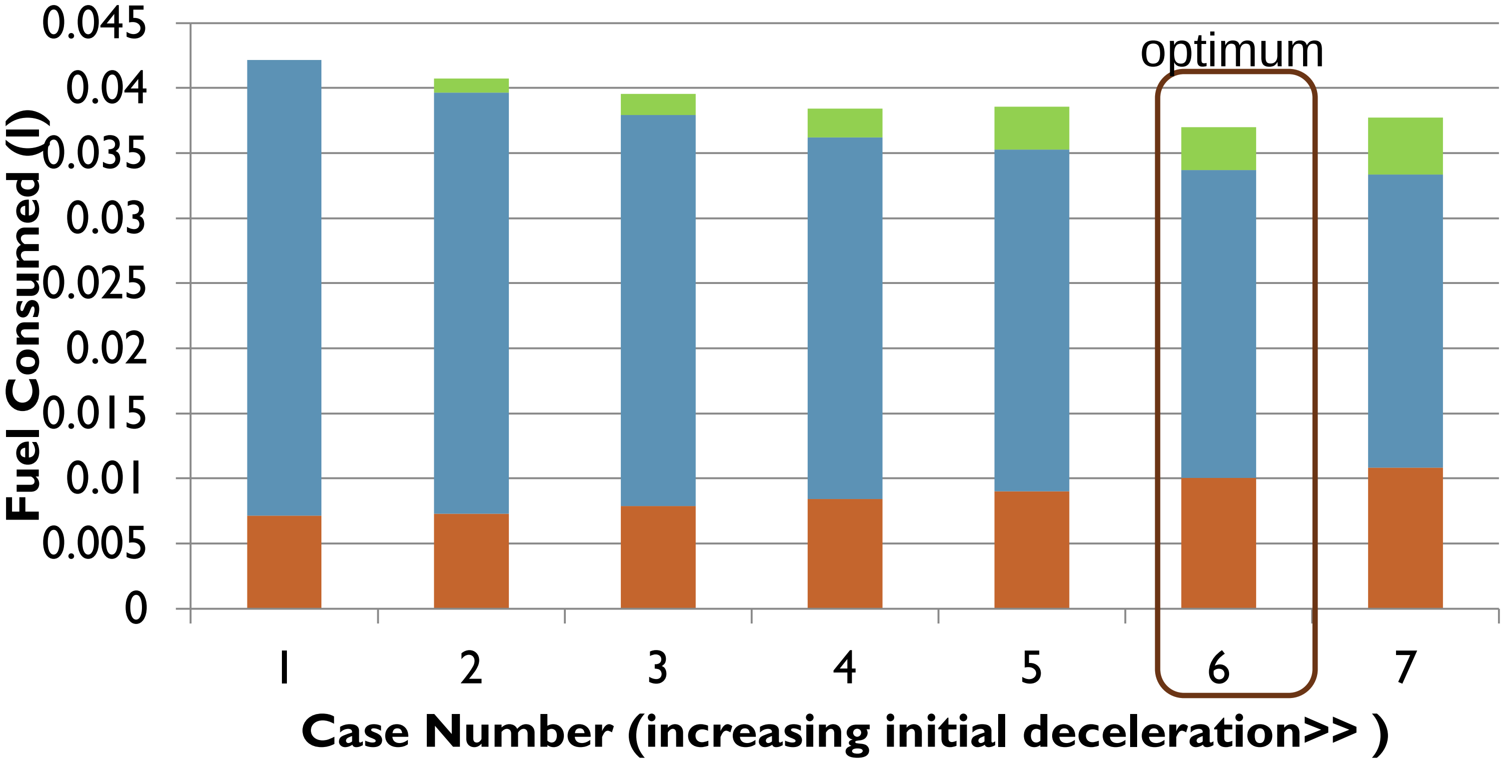
- Simulation was conducted for different approach speeds considering the following parameters:
  - TTG = t =14 s
  - DTI = x = 200 m
  - Approach speed = v_a = 20 m/s
  - Delay required = Δt = 4 s
  - d_{min} = 0.82 m/s^2 (computed)
  - d_{max} = 5.90 m/s^2 (limiting).

Example Illustration



Simulation Results

Fuel consumed in seven cases of 30% throttle by Chevy Malibu (l)



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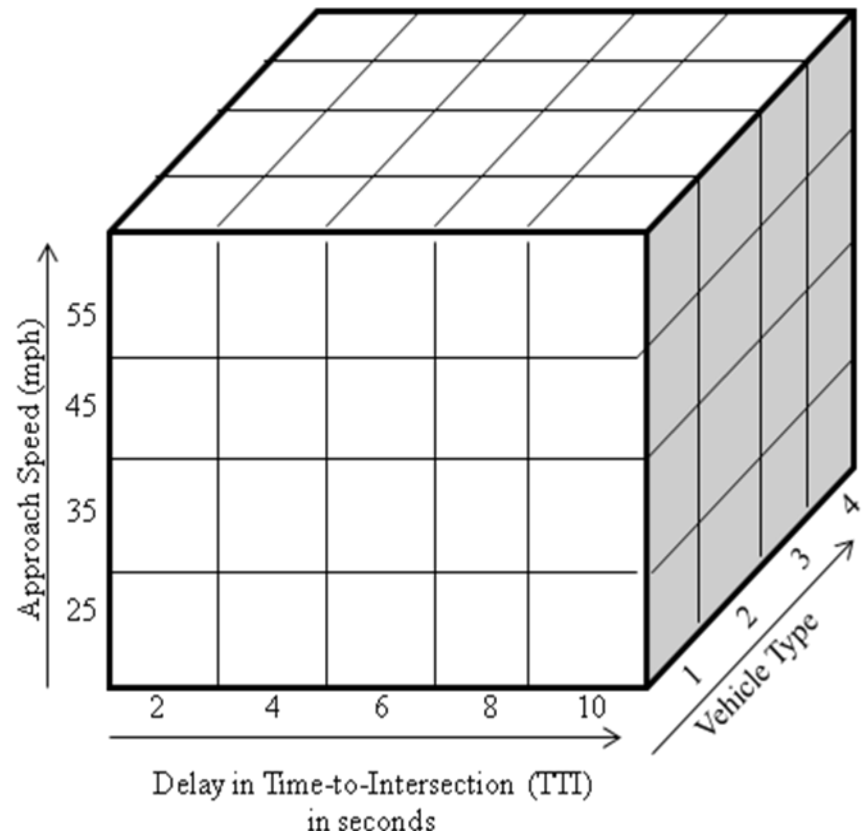
Case Studies

- Experiment repeated using various sets of
  - Approach speeds
  - Desired delay estimates
  - Vehicle Types
- 80 cases simulated maintaining a constant DTI of 200 m.



$$FC_i(ds) = FC_i(v_s \rightarrow v_a) + FC_{cruise}(v_a) \times [x_{\max} - x_{i-acc}]$$

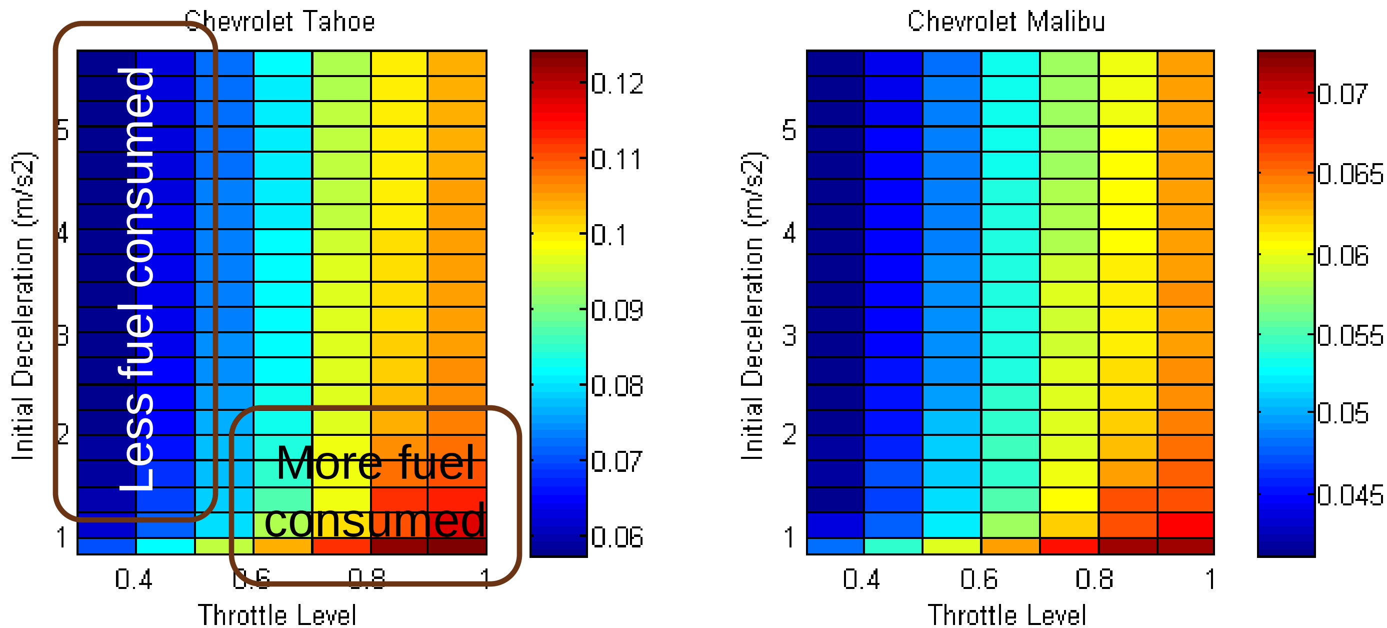
Case Studies

- Four vehicles were tested:
  - Vehicles selected were available at VTTI and thus were validated using field measurements

Vehicle Info	Vehicle 1 SAAB	Vehicle 2 Mercedes	Vehicle 3 Chevy	Vehicle 4 Chevy
Model	95	R350	Tahoe	Malibu
Year	2001	2006	2008	2007
Engine Size (L)	2.3	3.5	5.3	2.2
EPA Rating (City/Highway)	21/30	16/21	14/20	24/34
Fuel-optimal speed	45.9mph	37.3mph	37.3mph	41.6mph

Sample Results

(Fuel-consumption matrix)



Fuel Consumption Matrix (when v_a = 45mph and δt = 4 seconds)

Inference 1: The greater the acceleration level, the higher is the fuel consumed.

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Sample Results
(fuel consumed in ml at 20% throttle)

- Results from two separate simulated cases are shown below (for 20% throttle) and are color coded according to fuel consumed.

Va = 20m/s, TTG = 14s, DTI = 200m				
dec(m/s²)	SAAB	R350	TAHOE	MALIBU
0.8163	50.90	76.00	59.20	44.60
1	47.50	70.00	55.50	42.20
1.25	47.00	67.00	53.00	41.70
1.5	46.00	67.50	52.40	42.20
1.75	45.70	66.90	53.20	42.00
2	45.40	66.40	52.80	41.60
2.5	45.10	65.90	52.20	41.40
3	46.00	65.40	51.80	41.20
4	45.70	65.40	51.70	41.10
5	45.70	64.90	51.30	41.90

Va = 11m/s, TTG = 22s, DTI = 200m				
dec(m/s²)	SAAB	R350	TAHOE	MALIBU
0.1736	20.20	23.90	27.90	17.90
0.25	20.10	23.90	27.30	18.00
0.5	20.30	24.20	27.40	18.60
0.75	21.00	24.20	27.20	18.90
1	21.20	24.50	27.30	18.80
1.5	21.20	24.50	27.30	18.80
2	21.40	24.80	27.40	18.90
3	21.40	24.80	27.50	18.90
4	21.40	24.80	27.50	19.00
5	21.40	24.80	27.50	19.00

Inference 2: Fuel-optimal case may not always involve minimal deceleration level

Sample Results
(deceleration in m/s^2 in optimum case)

Fuel-optimal Speeds	
Chevy Tahoe	37.3 mph
Chevy Malibu	41.6 mph

Chevy Tahoe

		Approach Speed (mph)			
		25	35	45	55
Delay (s)	2	1.00	2.00	1.00	4.75
	4	5.75	3.50	5.75	5.00
	6	2.75	5.00	5.75	5.50
	8	3.25	5.75	4.50	5.75
	10	3.75	5.75	5.25	5.75

Chevy Malibu

		Approach Speed (mph)			
		25	35	45	55
Delay (s)	2	0.25	0.50	1.75	2.50
	4	5.75	1.25	5.75	3.00
	6	0.25	1.00	5.75	5.50
	8	0.75	5.75	5.75	5.50
	10	1.00	5.75	4.75	4.25

Inference 3:

Deceleration in fuel-optimal case is proportional to

(a) Approach Speed

(b) Delay to be induced in the trajectory

Sample Results

(% difference between worst case and best case)

SAAB 95

Delay (s)	Approach Speed (mph) 25	35	45	55
2	11%	70%	91%	104%
4	27%	54%	81%	86%
6	21%	43%	66%	71%
8	20%	43%	56%	60%
10	20%	35%	51%	59%

Chevy Malibu

Delay (s)	Approach Speed (mph) 25	35	45	55
2	10%	67%	88%	96%
4	27%	54%	76%	85%
6	20%	40%	64%	71%
8	19%	42%	57%	62%
10	22%	35%	52%	63%

Chevy Tahoe

Delay (s)	Approach Speed (mph) 25	35	45	55
2	21%	102%	134%	154%
4	38%	79%	117%	130%
6	30%	55%	102%	110%
8	28%	64%	89%	96%
10	27%	54%	81%	98%

Mercedes R350

Delay (s)	Approach Speed (mph) 25	35	45	55
2	19%	90%	110%	118%
4	38%	70%	93%	98%
6	30%	53%	78%	83%
8	28%	53%	67%	68%
10	29%	45%	62%	71%

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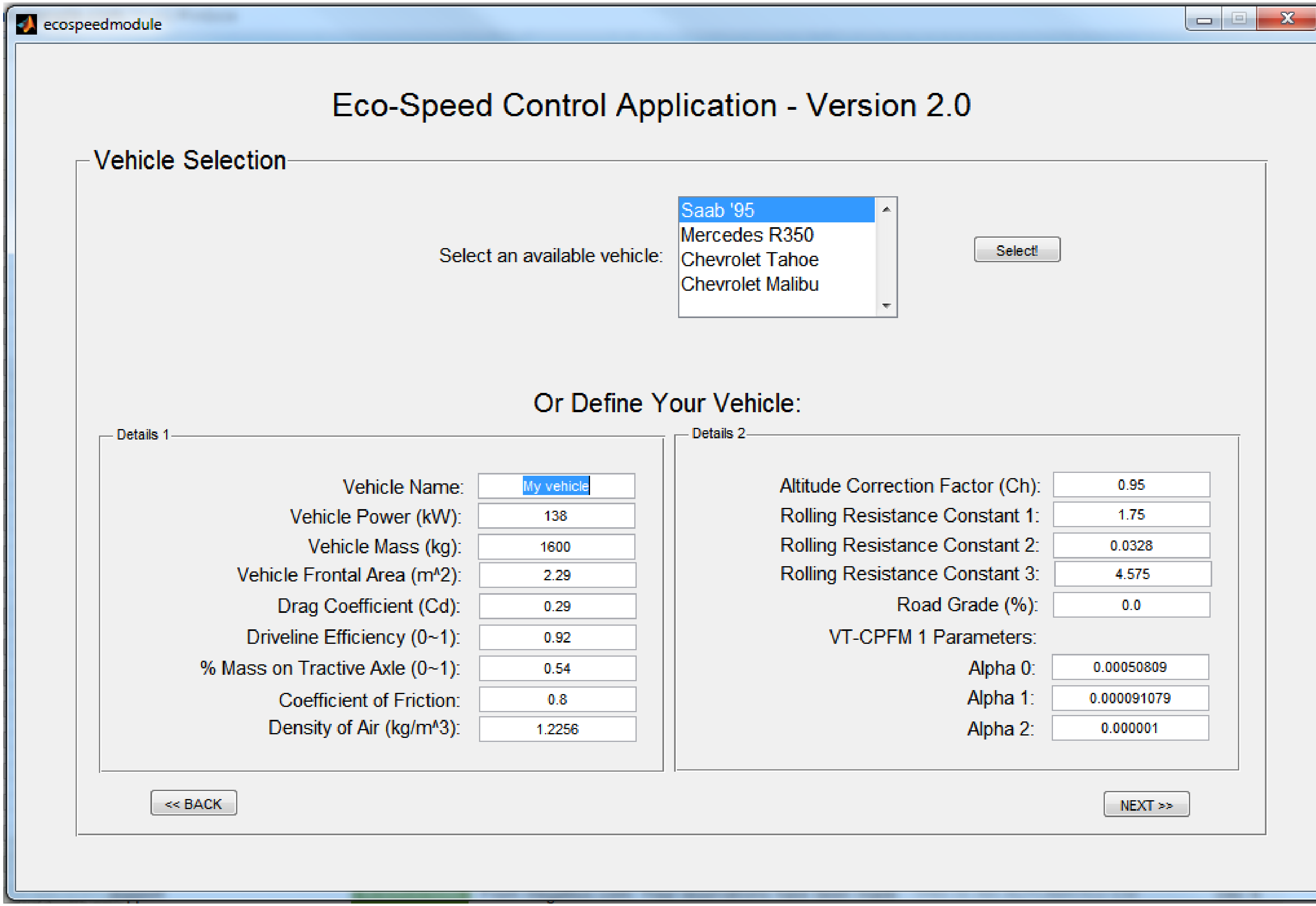
MATLAB Application



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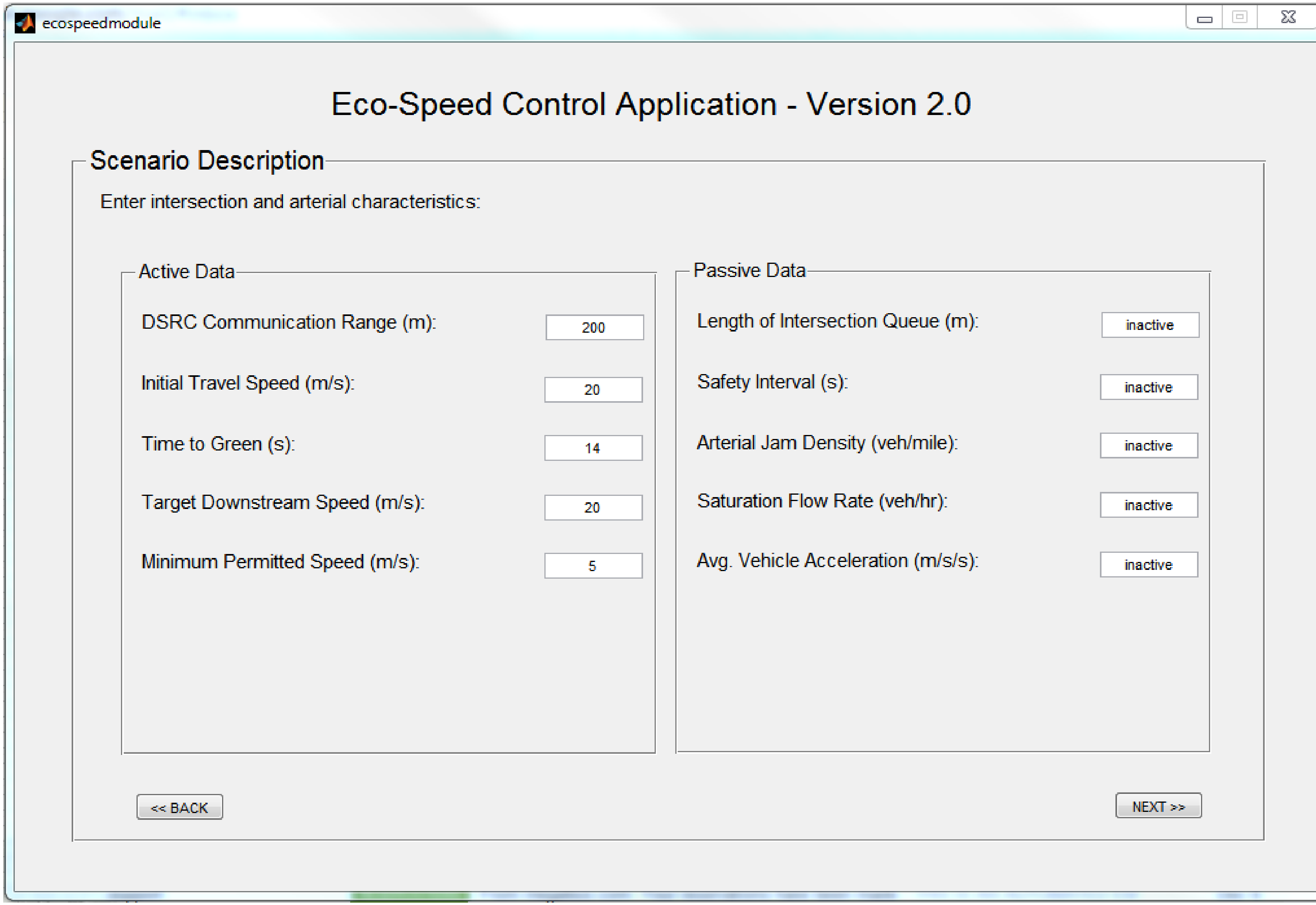
MATLAB Application



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MATLAB Application

ecospeedmodule

Eco-Speed Control Application - Version 2.0

Optimization Tool

My vehicle is ready for Eco-Speed Control. Hit 'Optimize!' button to find the most fuel optimal path.

Optimize!

	decel. (m/s/s)	vel. at int (m/s)	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1	0.8163	8.5714	0.0509	0.0559	0.0599	0.0635	0.0672	0.0711	0.0742	0.0744	0.
2	1	12.0000	0.0475	0.0514	0.0538	0.0566	0.0603	0.0631	0.0654	0.0678	0.
3	1.2500	12.8078	0.0466	0.0494	0.0526	0.0553	0.0583	0.0619	0.0630	0.0654	0.
4	1.5000	13.1774	0.0460	0.0487	0.0522	0.0547	0.0573	0.0606	0.0617	0.0641	0.
5	1.7500	13.3955	0.0457	0.0485	0.0518	0.0540	0.0564	0.0593	0.0623	0.0624	0.
6	2	13.5407	0.0454	0.0492	0.0510	0.0540	0.0564	0.0593	0.0604	0.0627	0.
7	2.2500	13.6446	0.0454	0.0490	0.0514	0.0544	0.0554	0.0597	0.0608	0.0632	0.
8	2.5000	13.7228	0.0451	0.0490	0.0507	0.0534	0.0554	0.0597	0.0609	0.0634	0.
9	2.7500	13.7839	0.0459	0.0485	0.0507	0.0534	0.0555	0.0581	0.0609	0.0635	0.
10	3	13.8329	0.0460	0.0485	0.0507	0.0534	0.0555	0.0581	0.0610	0.0611	0.
11	3.5000	13.9069	0.0460	0.0483	0.0503	0.0538	0.0558	0.0584	0.0614	0.0616	0.
12	4	13.9600	0.0456	0.0484	0.0503	0.0528	0.0557	0.0584	0.0594	0.0617	0.
13	4.5000	14.0000	0.0457	0.0484	0.0503	0.0528	0.0557	0.0585	0.0594	0.0618	0.
14	5	14.0312	0.0457	0.0484	0.0503	0.0528	0.0557	0.0585	0.0595	0.0619	0.
15	5.5000	14.0563	0.0453	0.0479	0.0503	0.0528	0.0557	0.0585	0.0595	0.0619	0.

The optimum case is decelerating at **2.5** m/s/s for **2.51087** seconds and past signal, accelerating at **20** % throttle.
Click RESULTS to plot the optimum velocity trajectory.

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RESULTS >>

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Conclusions

- Presentation demonstrates that objective function
  - Should not be simplified
    - Need to include a fuel-consumption model
      - Model should be robust
  - Need to incorporate entire downstream and upstream maneuver.
- Fuel-optimum trajectory is case-specific and depends on many factors.
  - Does not necessarily imply minimum deceleration level
- Potential savings for approaching vehicle:
  - 53% for sedans and 65% & 80% for the R350 & Tahoe.

Conclusions

- Deceleration upstream is case-specific.
- Initial deceleration is proportional to approach speed.
- Initial deceleration is also proportional to required delay.
- Acceleration depends on
  - Speed at intersection
    - Function of deceleration level
- In-vehicle module demonstrated with MATLAB application.
- Accelerating at lowest throttle level
  - Most fuel-optimal downstream action, but reduces discharge rate.
- Possible fuel savings is proportional to engine-size and approach speeds.

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Go Hokies!

Thank You!

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