JUNE 2, 2020

Project Task 7.A.3.2
EXPERIMENTAL EVALUATION OF ECO-DRIVING STRATEGIES

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OVERVIEW

TIMELINE

- Start: Feb 2018 (scope of work revised in Oct 2018)
- End: September 2019
- 100% complete

BARRIERS ADDRESSED

- Quantification of unproductive fuel consumptions at the national scale
- Methods to realistically estimate fuel saving for Eco-Driving strategies
- Identification of opportunities to address major fuel consumption causes

BUDGET

- Total project funding
- $460K / 2 years

PARTNERS

- Work collaboratively with San Jose State University
- The collected data, models and analyses from this study will become inputs to the relevant work under the SMART Mobility program

RELEVANCE

- **3.1 billion gallons of wasted fuel in the United States Due to Congestions** - the National Environment Mobility Scorecard (NMS) produced by the Texas Transportation Institute and INRIX
- **How much and where the unproductive fuel is consumed nationawide?** - Quantify unproductive fuel consumption and identify opportunities for fuel saving by applying Eco-Driving technologies
- **How much energy savings may Eco-Driving achieve realistically**? – Assess what Eco Driving technologies/ strategies are available and where they stand?
- **Scientific evidence of the benefits and impacts of Eco-Driving technologies –** Field experiment of a sample Eco Driving technology to support analytical findings

SUMMARY OF SCOPE AND APPROACHES

- Analyze gaps in the NMS estimation to where and how much wasted/unproductive energy** Eco-Driving may target
- Identify potential opportunities for Eco-Driving strategies and access their energy benefits and environmental impacts
- **Collect and analyze real-world data to establish methods for assessing energy consumption at arterial corridors and local intersections to support analyses of unproductive fuel and Eco-Driving opportunities**
- **Experimentally assess the benefits of Eco-Approach and Departure (EAD) strategies and impacts to surrounding traffic**

Year One Tasks

Task 1: Assessment of Eco-Driving Strategies

Task 2: Field Data Collection

Year Two Tasks

Task 3: Data Analyses (a signalized corridor & un-signalized Intersections)

Task 4: Field Testing of EAD

****Unproductive Energy Consumption** – the fuel/energy consumed in addition to the baseline fuel consumption due to driving at speeds lower or higher than the prescribed speed limit, with unnecessary decelerations, accelerations, and stops

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

1. Identified large gaps between unproductive fuel and the wasted fuel estimated in the National Mobility Scorecard (Year 1)
2. Reviewed existing work on Eco-Driving technologies and formulated a field-wide perspective on the status, estimation gaps, and research & development need (Year 1)
3. **Two days of vehicle trajectory level traffic data were collected at ten signalized intersections along a test corridor in the city of San Jose and four intersections (including comparable signalized, stop sign controlled, and roundabout intersections) in the city of Pleasant Hill. Additional data were collected at a few unsignalized intersections in other California cities (Year 2)**
4. **Field evaluation of EAD was conducted using five experimental vehicles at the testing corridor in San Jose, in conjunction of the field traffic data collection (Year 2)**
5. **Data processing tools were developed to process the traffic data and to support fuel consumption analyses. Extensive traffic analyses were conducted for one signalized intersection and one unsignalized intersection (Year 2)**

A CASE STUDY

Eco Approach and Departure (EAD)

Knowledge gained

- High saving benefits were reported through simulation and tested at isolated testing intersection; Only 10% work involves testing, with limited runs.
- EAD works better with fixed timing signals than actuated and adaptive signals
- EAD becomes less effective when the signals are well coordinated or in heavy traffic

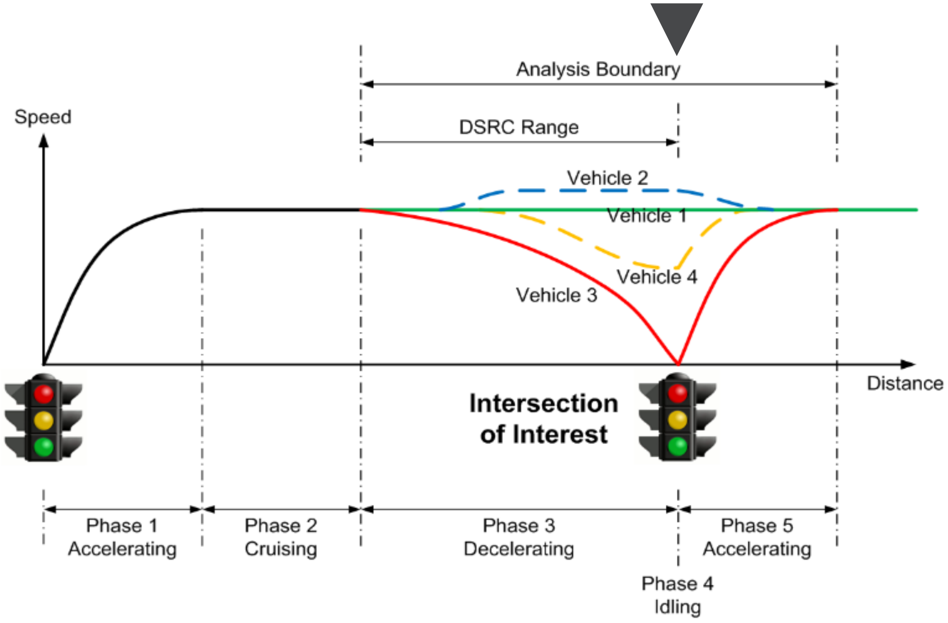
Issues

- Different evaluation methods and operating conditions
- Large variation of system performance (e.g., signal timing prediction for fixed timing vs. adaptive)
- Benefits affected by many factors (e.g., traffic, human factors, vehicle, etc) – order of magnitude analysis
- Distraction issue needs to be addressed
- Impact of 'EAD driving behavior' to other vehicles

Authors /Ref.	Test site (w/ traffic [T] or w/o traffic [I])	#_signal/length/speed	Fuel saving
Koukoumidis et al. (2011)	Cambridge, MA	3; 0.3mi, 30mph	20.3%
Barth et al. (2012)	Richmond Field Station, CA	1, 0.2mi, 25mph	13.6%
Atlan et al. (2017)	TFHRC in VA (ACC w/EAD)	1, 0.2mi, 20-25mph	2~46% Vs. driver -6~50% Vs. driver with EAD
Meng et al. (2015)	Palo Alto, CA	10, 1.7mi, 35mph	3%~4%
Mintsis et al. (2017)	Thessaloniki, Greece (341 taxis tested for months)	12, 1.6mi, 37mph	6.0% -9.1%
Hao et al. (2019)	Palo Alto, CA	10, 1.7mi, 35mph	2% All trips 6% (less vehicle following @<10m)

ECO APPROACH AND DEPARTURE

- **Passing through during green phase (V1)**
- **Eco Approach and Departure at the end of green phase (EAD-G):** to support slightly higher speed to pass intersection without stop (V2)
- **Eco Approach (EA-G) at the end of Green phase:** to support earlier release throttle and gentler deceleration: (V3)
- **Eco Approach and Departure at the end of red (EAD-R):** to support gentler deceleration and accelerate to pass intersection without stop (V4)



FIELD EVALUATION OF EAD

Objectively assess the benefits of Eco-Driving technologies at event, trip, system levels

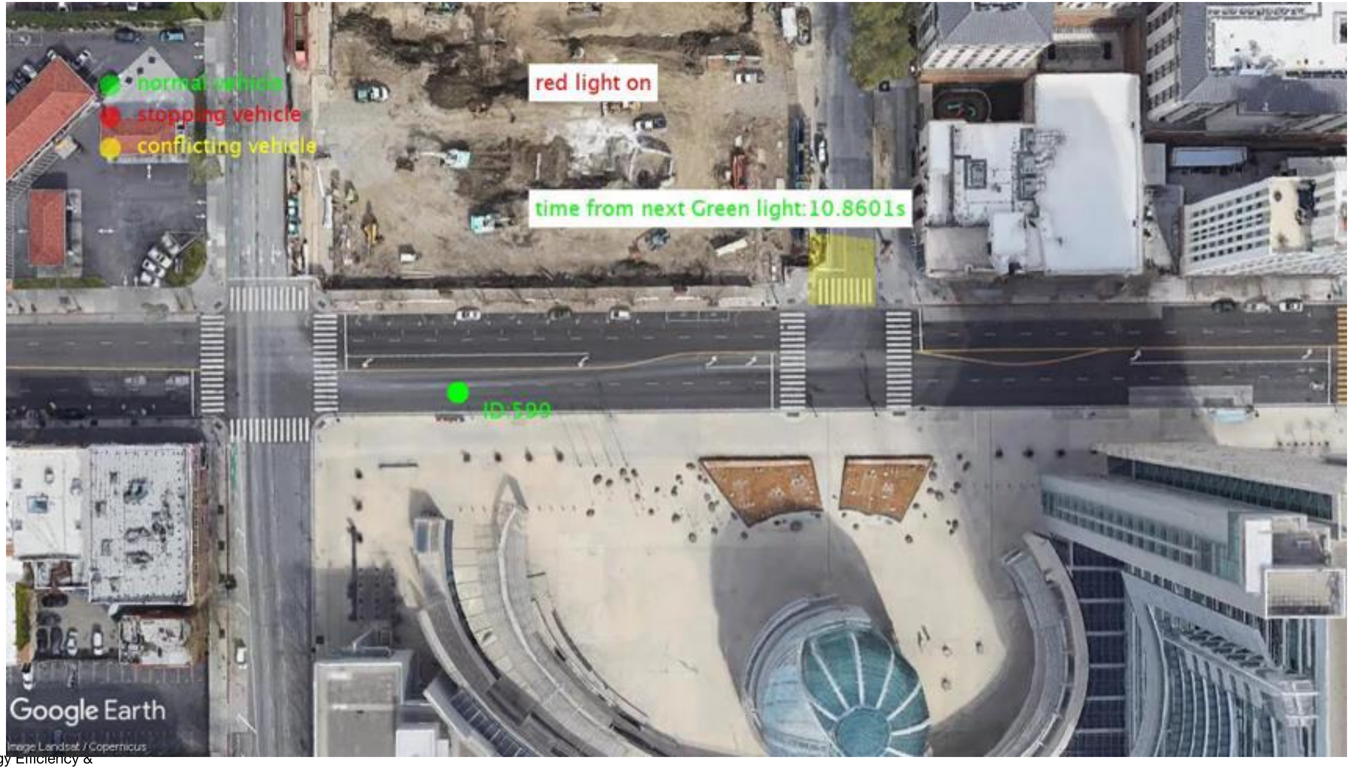
- ○ Opportunities for EAD to function
- ○ Realistic expectation of fuel saving benefits
- ○ Impact to surrounding traffic

- Evaluation method
  - ○ Side-by-side performance comparison with/without treatment
- Test vehicles
  - ○ One vehicle with multiple sensors: Lidar, 8 cameras, CAN, gyro, GPS
  - ○ 4 rental cars
- Enlighten EAD App
  - ○ App by Connected Signals
  - ○ Signal status data provided by city of San Jose
  - ○ Red phase countdown
  - ○ Green arrow (released version)/Green phase countdown (test version)
  - ○ Speed (range) recommendation

Bird view videos are collected from the rooftop of 6 Buildings

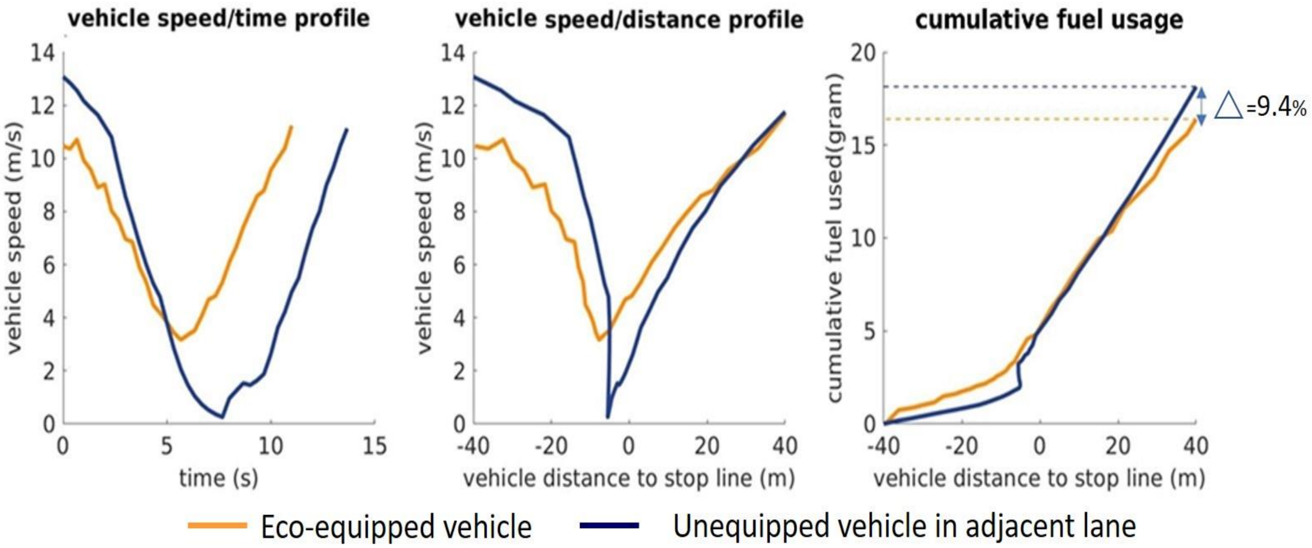
EAD SCENARIO EXAMPLES

EA-G Example: An EAD Equipped Vehicle Saves Fuel Over an Unequipped Vehicle



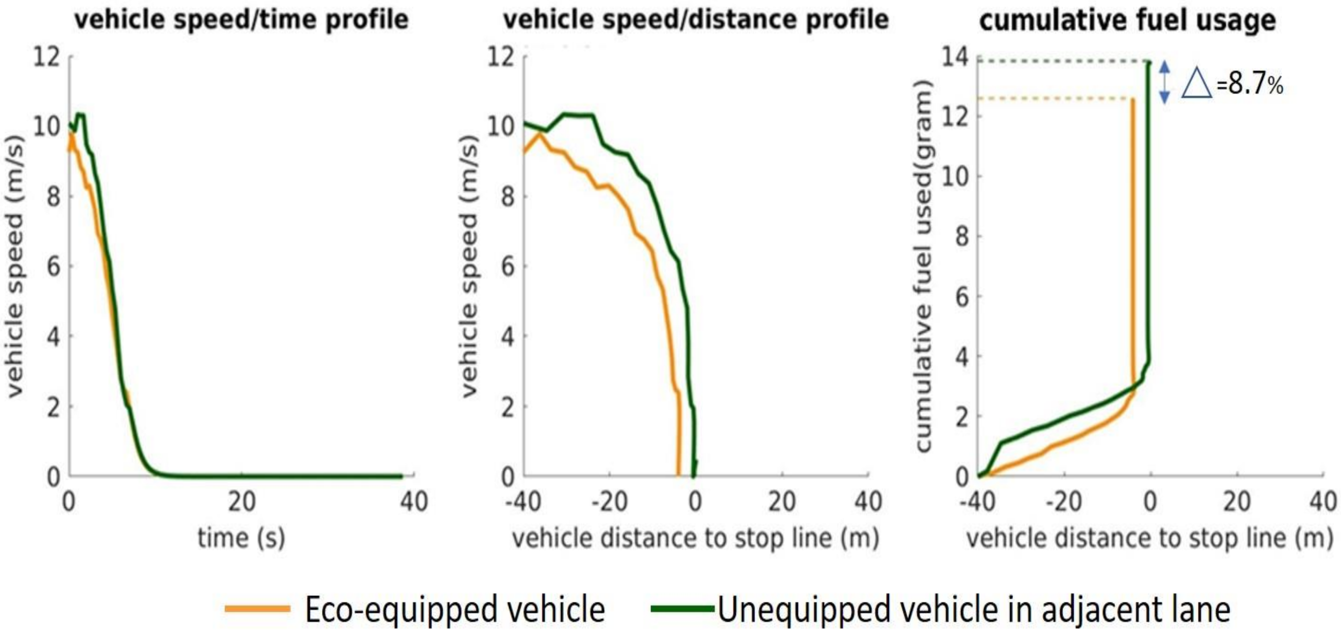
EAD SCENARIO EXAMPLES

EAD-R Example: Eco-Equipped Vehicle avoids a Full Stop



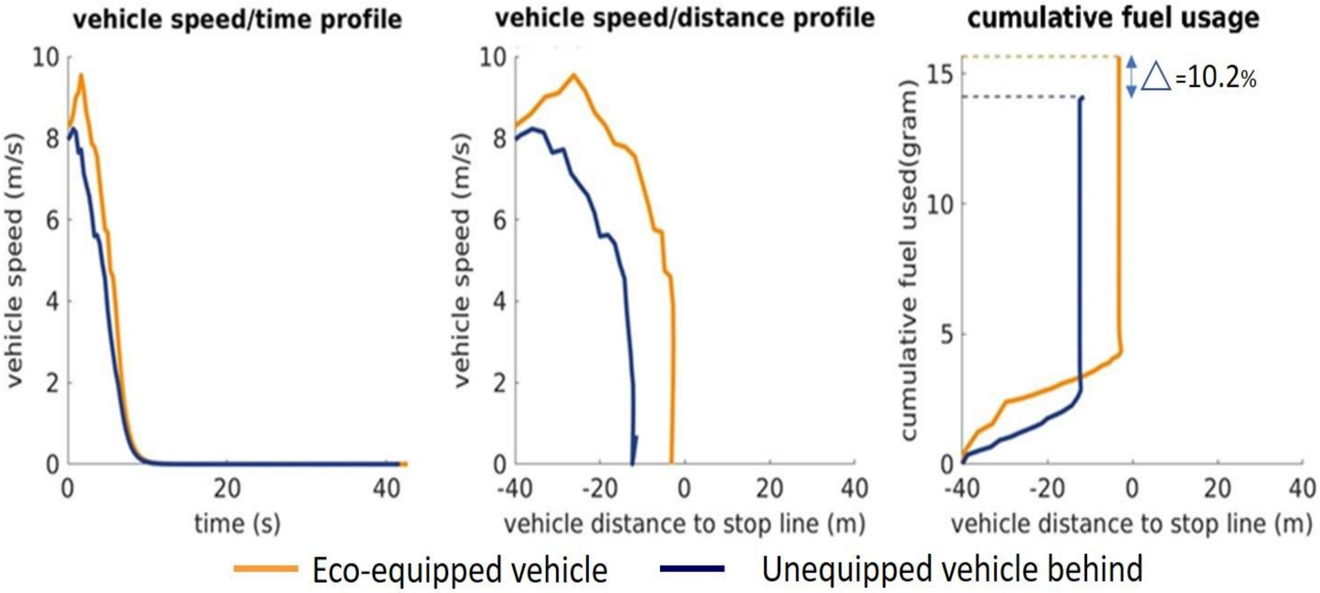
EAD SCENARIO EXAMPLES

EA-G Example: An EAD Equipped Vehicle Saves Fuel Over an Unequipped Vehicle



EAD SCENARIO EXAMPLES

EA-G Example: An unequipped vehicle saves fuel by following an Eco-Equipped Vehicle



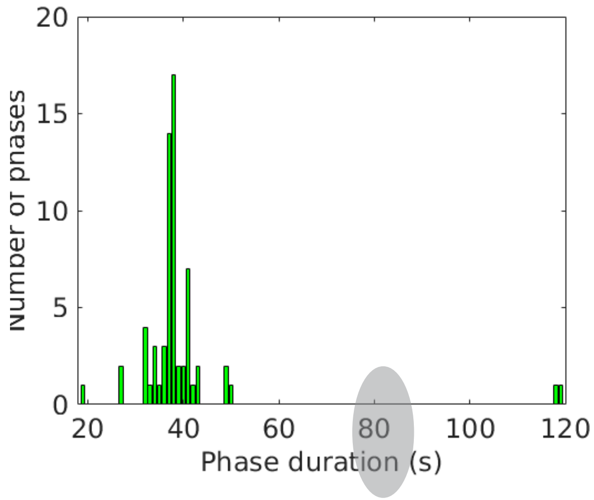
FIELD EVALUATION RESULTS

	Event	# of occurrences (in 10 hours)	% of Arrivals for Eco-equipped vehicles	Average Fuel Consumed per Occurrence (grams)	Cumulative Fuel Consumed (grams)	Average Fuel Saving due to EAD (grams)
All Vehicles	Cruise	2549		16.6	42313	
	Stopped	2747		26.3	72246	
Eco-equipped Vehicles	Arrive during green phase	52	63.4%			
	Arrive during red phase	17	20.7%			
	Arrive at end of red phase (EAD-R)	3	3.7%	21.3	63.9	15
	Pass at end of green (EAD-G)	0	0%			
	Arrive at end of green (EA-G)	10	12.2%	22.8	228	35

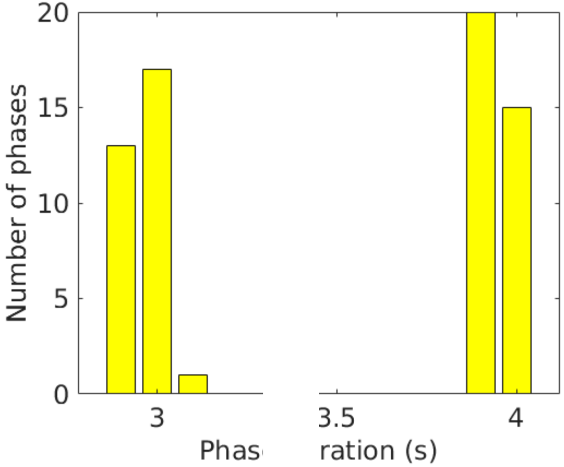
* FHWA, Summary of Travel Trends 2017 National Household Travel Survey

STUDY OF SIGNALIZED INTERSECTION

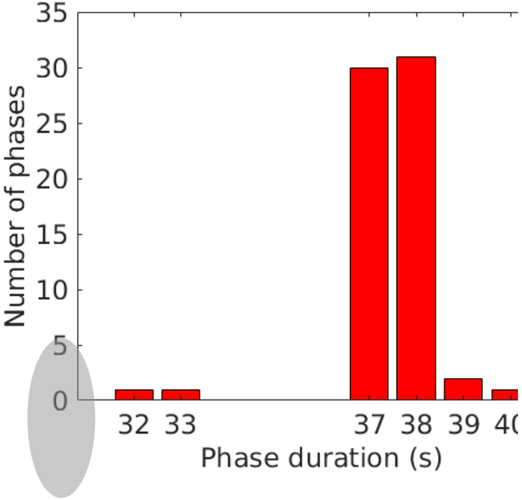
The opportunities for vehicles to arrive at the end of green phase or at end of red phase are low



Green light interval distribution
Mean: 40.55s
Std Dev: 14.78s



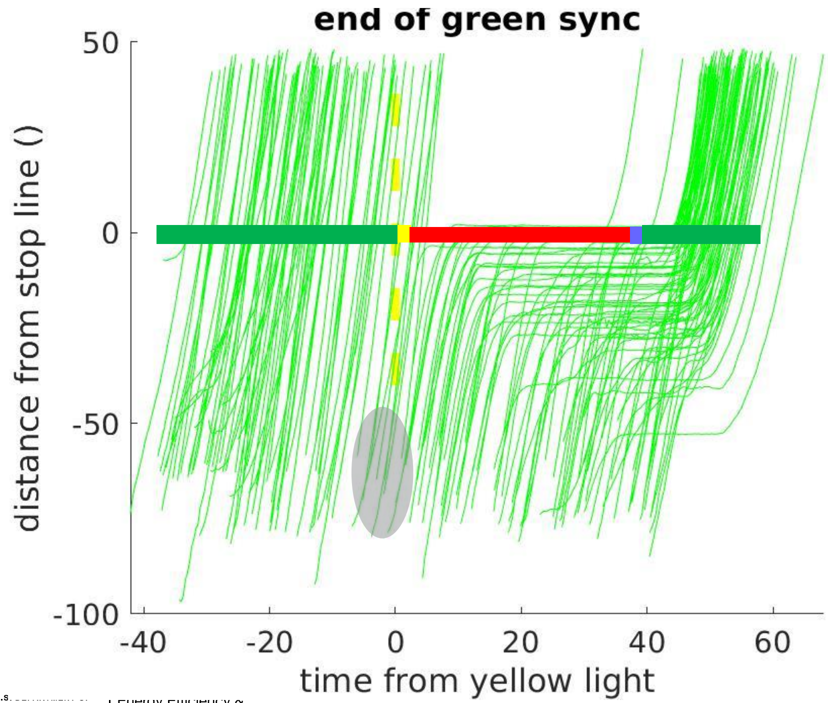
Yellow light int al distribution
Mean: 3.53s
Std Dev: 0.50s

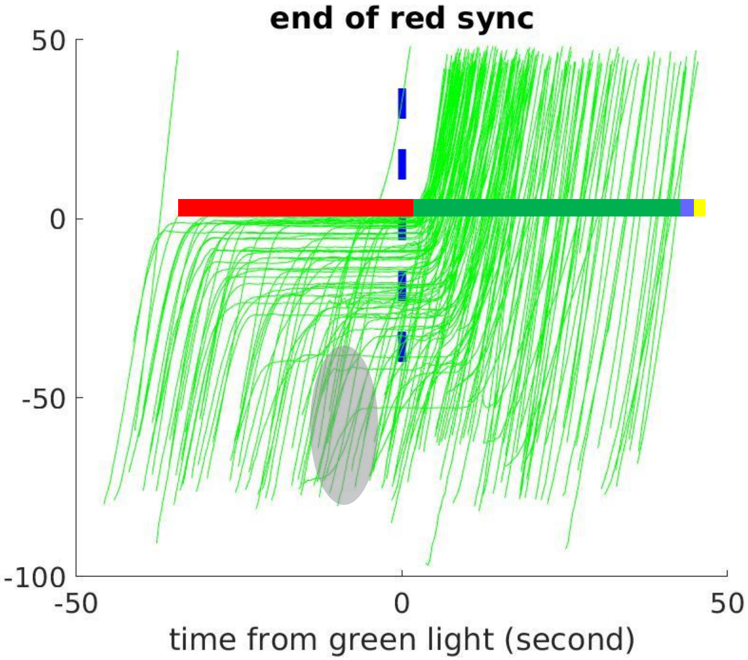


Red light interval distribution
Mean: 37.92s
Std Dev: 0.85s

STUDY OF SIGNALIZED INTERSECTION

The opportunities for vehicles to arrive at the end of green phase or at end of red phase are low





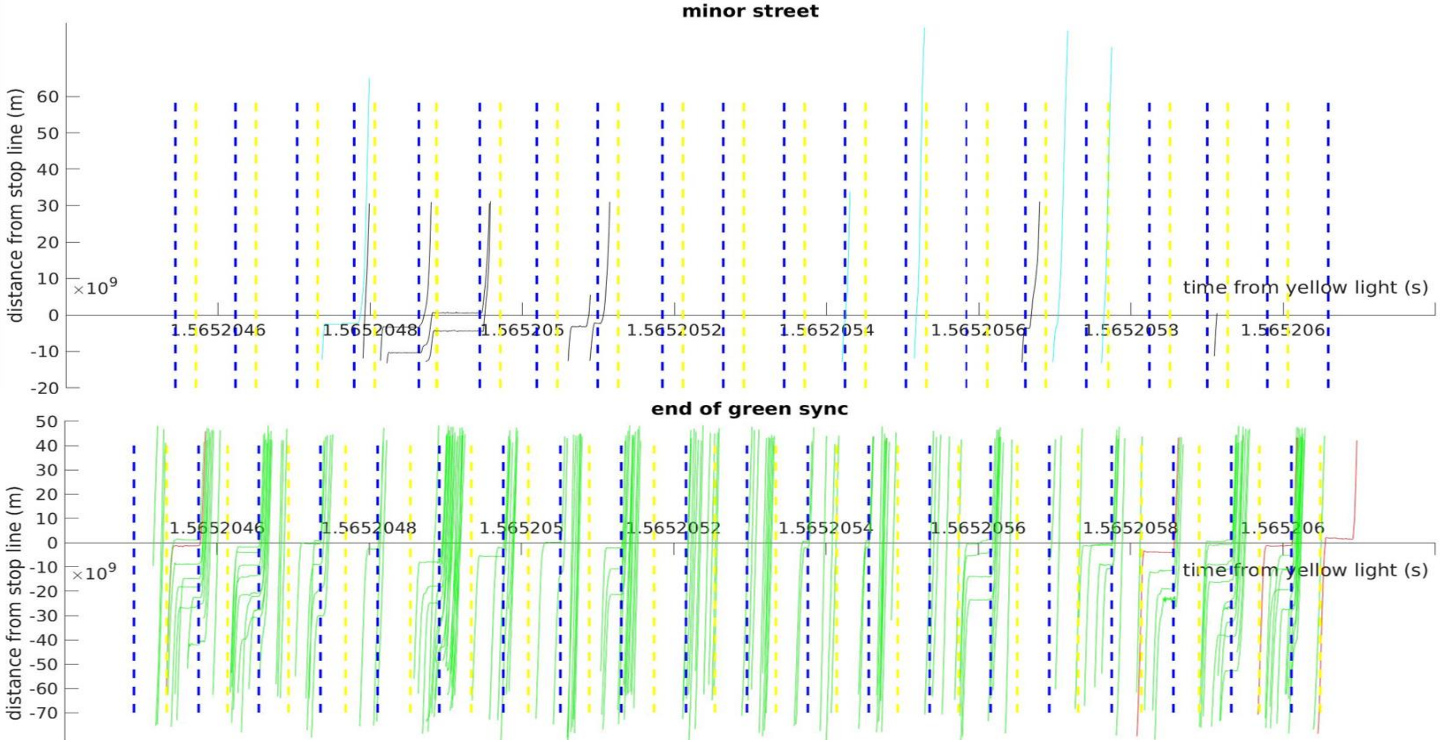
FIELD EVALUATION RESULTS

- **Fuel Saving Benefits at Event Level**
  - A moderate fuel savings of 10% to 20% per EAD event, as compared with adjacent unequipped vehicles
  - EAD strategies were applicable for only ~15% of the arrivals (including ~ 3-4% without stopping at the end of red phase due to EAD and ~10-12% with gentler deceleration at the end of the green phase)
- **Analysis of Fuel Savings Benefits at Trip Level**
  - EAD may facilitate < ~1% saving of fuel consumed for an average trip*
- **As the opportunities for vehicles to arrive at the end of green and at end of red are low, and because of the uncertainties for predicting the signal phase change, the fuel saving benefit of EAD at intersection level is insignificant**

* FHWA, Summary of Travel Trends 2017 National Household Travel Survey

STUDY OF SIGNALIZED INTERSECTION

Minor street signal phases are often not productively utilized, causing the delays and unproductive fuel consumption for vehicles at the main approach

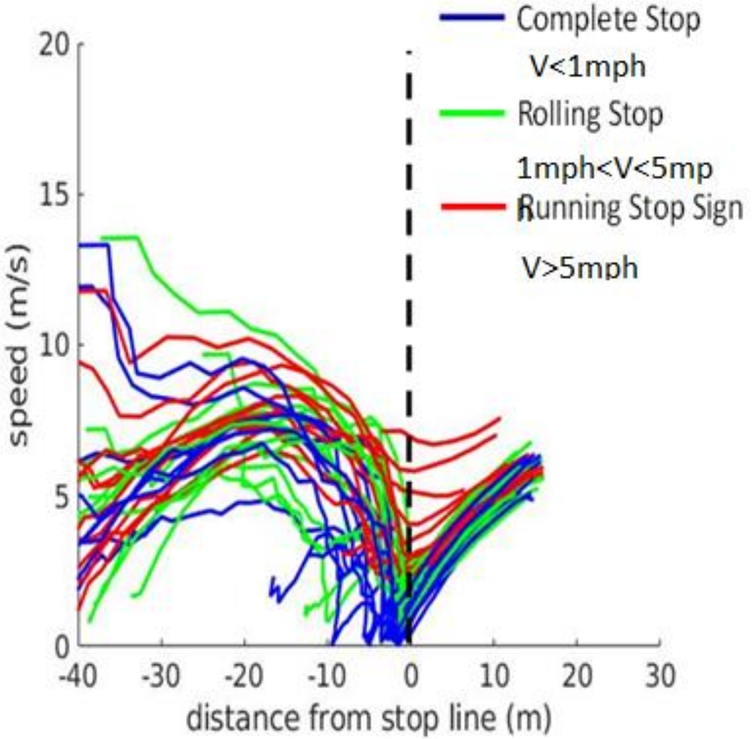


UNPRODUCTIVE FUEL CONSUMPTION AT INTERSECTION LEVEL

- **Unproductive fuel consumption at the testing intersection (due to unproductive stopping and idling)**
  - Among ~50% of the vehicles stopping at the intersection during the red phase
    - ~30% of the vehicle stops encountered other vehicles at the conflicting approaches
    - the remaining ~70% of vehicle stops observed within the evaluation period encountered no conflicting vehicles
  - Estimated unproductive fuel consumption accounts for up to 30% of total fuel consumption at the test intersection
- **Unnecessary stops is caused by inefficient traffic control at signalized intersections**
  - suboptimal detection of approaching vehicles at intersections
  - traffic control not being able to adapt to real-time traffic conditions
- **Unproductive fuel consumption can potentially be mitigated via advanced detection of vehicles at intersections or with connected vehicle technologies**

STUDY OF UNSIGNALIZED INTERSECTION

- ~30% of all the vehicles made a full stop at the case study intersection, mainly due to presence of vehicles at conflicting approaches
- The rate of rolling stops and stop sign running has an inverse relationship with the rate of conflicting vehicles
- The unnecessary stops result in substantial unproductive fuel consumption (> ~15% of fuel consumed at the testing intersection) and significant travel delays
- Fuel saving benefits may be achieved with roundabout, or Connected Vehicle technologies



RESPONSE TO PREVIOUS YEAR REVIEW COMMENTS

It could use improvement by refining the project's definition of "unproductive" because the productivity benefits regarding driver safety (in the case of stop signals) and roadway throughput (for speeds above 65 miles per hour [MPH]) are not considered in the analysis.

This is a very important point. The safety and efficiency are essential to the transportation systems. In the future (subject to funding levels), we plan to incorporate the analysis of unproductive fuel consumptions in the national performance measures that deal with all spectrum of MOEs.

A broader eco-driving technology in-use data set would likely be helpful but is not in the scope of the project.

We have included review of a FOT EAD, but there hasn't been large in-use data at this time. We are interested in collecting in-use data set for the proposed work when a broader set of Eco Driving technologies are assessed.

Much clearer mapping and data product definitions of this project's outputs as inputs to the other EEMS or DOT R&D tasks… and the inputs that this project receives from other projects or partners. unique efforts and capabilities. Adding this structure will likely help to increase the utility and value of this project team's./One area of unique value added is the potential to help inform and validate other EEMS modeling projects.

Since the Eco Driving project was started in the middle of SMART Mobility Phase One Program, it was difficult to arrange this project to interface with other projects that were started more than a year earlier. If selected, we plan to include Texas A&M researchers and work with ANL colleagues interactively in the SMART Mobility Phase Two.

SUMMARY

- **At least ~10 Billion gallons of unproductive fuel were consumed annually, including more than 3 billion gallons of fuel consumed unproductively at intersections**
- **Findings on field evaluation of benefits of EAD and unproductive fuel consumptions at intersections**
  - Fuel saving benefits of EAD is insignificant at both trip level and intersection level, offering little for mitigating unproductive fuel consumption
  - Vehicle stops and idling when no conflicting vehicles present at conflicting approach are the major cause for unproductive fuel consumption at signalized intersections
  - Majority of vehicles arrived at stop-sign controlled intersections do not encounter travelers at conflicting approaches, resulting in substantial unproductively fuel consumption
  - Fuel saving benefits at both signalized and unsignalized intersections could be achieved via effective detection and CAV supported traffic control and coordination among vehicles
- **The with/without evaluation approach supports objective assessment and is appropriate for evaluation of Eco Driving technologies**

COLLABORATIONS

SMART Mobility Phase I Project Partners

- Lawrence Berkeley National Lab/University of California at Berkeley – ITS, Connected Vehicle and vehicle automation, traffic data and traffic control
- San Jose State University – transportation systems analysis, statistical analysis

In the future (subject to funding levels), we plan to collaborate with

- Lawrence Berkeley National Lab/University of California at Berkeley – ITS, Connected Vehicle and vehicle automation, traffic data and traffic control
- Texas Transportation Institute, Texas A&M University – transportation planning, analysis, emission analysis
- Argonne National Lab – Energy systems, vehicle technologies

REMAINING CHALLENGES AND BARRIERS

- **National level data is needed for support of the analyses of wasted and unproductive fuel consumption at the regional and national levels.**
- **Additional field data collection and analyses are needed for identified major unproductive consumption scenarios at intersections and freeways. Eco-Driving Countermeasures for addressing these major unproductive fuel consumption scenarios needed to be identified**
- **Based on the knowledge gained from evaluation of EAD, scientific evidence needs to be produced for the other Eco Driving technologies that have potential to address major unproductive fuel consumption scenarios**

FUTURE WORK BEYOND THIS PROJECT**

Continue to assess unproductive fuel consumption and benefits of Eco-Driving technologies through real world data and experimentation

- Extend the analyses of wasted and unproductive fuel consumption at the regional and national levels using extensive national traffic data, supplemented with field experiments. The goal is to incorporate the unproductive fuel consumption estimates and fuel saving goals into the national performance measures
- Further analysis to identify various components of unproductive energy consumption and countermeasures that offer the most potential to minimize wasted fuel in our transportation system
- Field data collection and analyses of selected Eco-Driving strategies to produce statistically significant evidence of energy reduction benefits

Any proposed future work is subject to funding levels

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MOBILITY FOR OPPORTUNITY

FOR MORE INFORMATION

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OAK RIDGE National Laboratory

SUMMARY OF YEAR 1 STUDY

Assessment of ITS Supported Eco-Driving Strategies

Assessment

Literature was reviewed, covering technical development in the areas of Eco Approach and Departure, platooning, CACC, Eco-Route guidance, etc.

Findings

- Study results vary significantly, many with unrealistically overestimated benefits
  - Most of studies are conducted through analyses/simulation, few with limited field tests
  - Nearly all studies intend to search for the best possible performance/maximum benefits
- Difficult to make apples-to-apples comparison among research results
  - Different baselines, assumptions and application scenarios were used
  - Different fuel saving models were used in the applications and evaluations
- Mostly focus on fuel saving for subject vehicles, with little or no consideration of impacts to surrounding vehicles and the efficiency/safety of the overall traffic system

Urgent needs for studies of deployment issues

- Scientific evidences through field evaluation under real-world conditions are needed
- Deployment issues, including policies, operation and safety need to be studied

SUMMARY OF YEAR 1 STUDY

Analysis of Unproductive Fuel Consumption

The unproductive fuel consumptions are at least the same order of magnitude as the wasted fuel estimates reported in the National Mobility Report (NMR)

Estimations gaps	Unproductive fuel consumptions (gallons)
Speed higher than 65 mph	0.5 to 5 billion
Unnecessary stops at stop signs	2 - 3 billion
Idling	6 billion
Approximate stop and go with lower average speed	10% of fuel wasted for stop and go traffic**
Approximate intersection traffic with average speed	Up to 50% of fuel wasted at congested signalized intersections**

At least ~10 Billion gallons of unproductive fuel is consumed annually, in addition to the NMR estimated 3.1 billion gallons wasted fuel

SUMMARY OF YEAR 1 STUDY

Assessment of ITS Supported Eco-Driving Strategies (Task 1)

Energy Dissipation Assessment -- Dissipated energy (power-to-wheel) that Eco-Driving may address:

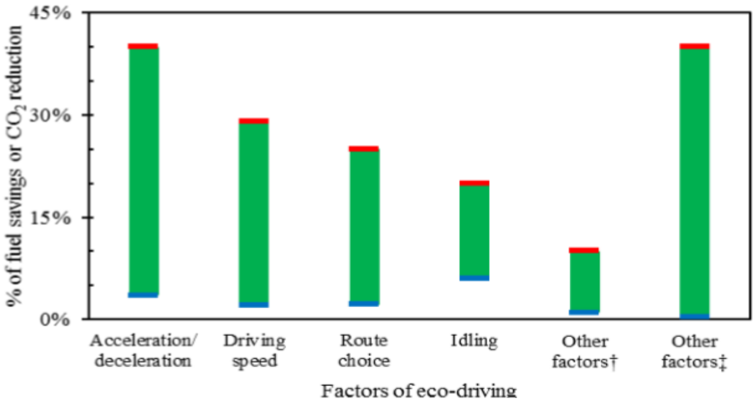
~ 30% for combustion engines

~ 40% for hybrid vehicles

~ 65% for electric vehicles

Literature review on Development-to-date on Eco-Driving technologies:

- ❑ Substantial work has been conducted by many to implement Eco-Driving strategies:
  - Avoid harsh deceleration/acceleration
  - Drive at appropriate speeds
  - Reduce air drag
  - Minimize idling
  - Select less congested routes
- ❑ Results from these studies vary significantly,often with unrealistically high fuel saving benefits



Yuhan Huang, Elvin Cheuk Yin Ng, John L Zhou, Nicholas Surawski, Eco-driving technology for sustainable road transport: A review, Renewable and Sustainable Energy Reviews, 2018

Further Research and Development are needed to bring Eco−Driving to real world

UNPRODUCTIVE FUEL CONSUMPTION AT INTERSECTION LEVEL

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- **Unproductive fuel consumption at the testing intersection (due to unproductive**

Event		Number of Arrivals							Average Fuel Consumption		Unproductive Fuel Consumption
		07:30 -08:30	08:30 -09:30	09:30 -10:30	10:30 -11:30	11:30 -12:30	12:30 -13:30	Average	Per arrival (gram)	Hourly average (gallon)	Hourly Unproductive fuel (gram/gallon)
Arrival at Red Phase	Conflicting vehicles present	25 7.0%	33 7.2%	61 12.8%	75 14.5%	103 14.5%	51 19.2%	58 13.2%	28.7	0.51	0/0
	No conflicting vehicles present	172 48.5%	220 48.0%	150 31.5%	177 34.2%	224 41.8%	72 24.7%	169 38.6%	25.1	1.31	1437/0.45
Arrival at Green Phase (passing through)		157 44.4%	205 44.7%	265 55.6%	265 47.8%	208 38.9%	168 57.7%	211 48.2%	16.6	1.08	0/0
Total number of arrivals		354	458	476	517	535	291	439			

STUDY OF UNSIGNALIZED INTERSECTION

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Summary of Findings

	Event	# and % of arrivals/hour					Average fuel consumption per arrival (Grams)	Average hourly fuel consumption (gallon)	Unproductive Fuel Consumption (gallon)
		East	West	South	North	Total			
Full stop	w/conflicting vehicles	68 22.9 %	49 14.16%	14 15.0 %	20 16.1 %	151 17.56%	20.4	0.81	0
Full stop	w/o conflicting vehicles	20 8.8%	29 10.8%	15 16.1 %	15 12.1 %	79 9.1%	17.6	0.36	0.21
Rolling vehicles	w/conflicting vehicles	34 11.4 %	31 8.9 %	5 5.3 %	16 12.9 %	86 10.0 %	15.9	0.36	0
Rolling vehicles	w/o conflicting vehicles	97 34.1%	132 38.1 %	33 35.4 %	33 26.6 %	295 34.3 %	14.6	1.13	0.54
Running vehicles	w/conflicting vehicles	11 3.7 %	22 6.3 %	3 3.2 %	5 4.0 %	41 4.7 %	13.4	0.14	0
Running vehicles	w/o conflicting vehicles	67 22.56%	83 23.99%	23 24.73%	35 28.23%	208 24.19%	12.2	0.67	0.25
	Reference steady speed vehicle @ 22mph						7.6		
	Total	297	346	93	124	860			

*https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa09027/resources/Iowa%20Traffic%20and%20Safety%20FS-%20Unsignalized%20Intersections.pdf