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Pillar: CAV

U.S. DEPARTMENT OF ENERGY

SMARTMOBILITY

Systems and Modeling for Accelerated Research in Transportation

Project Task 7.A.3.2
Experimental Evaluation of Eco-Driving Strategies

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OVERVIEW

TIMELINE

- Start: Feb 2018 (scope of work updated in Oct 2018)
- End: September 2019
- 50% 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
- $400K

PARTNERS

- 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 due to congestions** – National Mobility Scorecard (NMS) by the Texas Transportation Institute and INRIX, a widely referenced study on traffic congestion in the United States
- **Analyze how much and where unproductive energy** is consumed? -** Quantify unproductive fuel consumptions under various operation scenarios (above and beyond of NMS studies); and identify opportunities for fuel saving through Eco-Driving strategies/technologies
- **Identify how much energy savings may Eco-Driving achieve realistically? –** Assess what Eco Driving technologies/ strategies are available and where they stand?
- **Produce scientific evidences of the benefits and impacts of Eco-Driving technologies –** Field experiment of a sample Eco Driving technology to support analytical findings

****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**

APPROACH and Milestones

Analyses: Identify and quantify unproductive fuel consumptions; analyze where and how much of the unproductive energy consumptions Eco-Driving may target (Task 1)

Collection of Real World Traffic Data: Collect field data at signalized arterial corridor and unsignalized intersections to support analyses of unproductive fuel and Eco-Driving opportunities (Task 2 and Task 3)

Field Experimentation of Eco Driving Technology: Field test a prototype Eco Approach and Departure system in a traffic to collect before-and-after data on movements and fuel consumption of the subject vehicle, the movements of surrounding vehicles, and the traffic in the corridor (Task 4)

Tasks

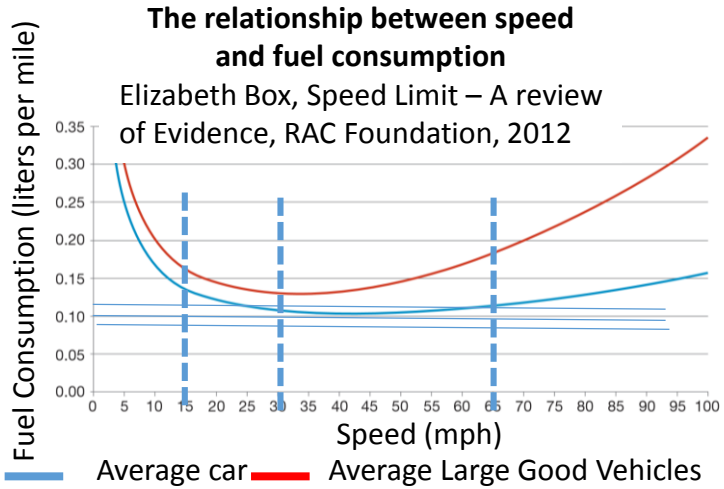
	2018			2019								
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Task 1. Assessment of Eco-Driving Strategies												
Task 2. Field Data Collection												
Task 3. Data Analyses (for a signalized corridor and unsignalized Intersections)												
Task 4. Field Testing of EAD												

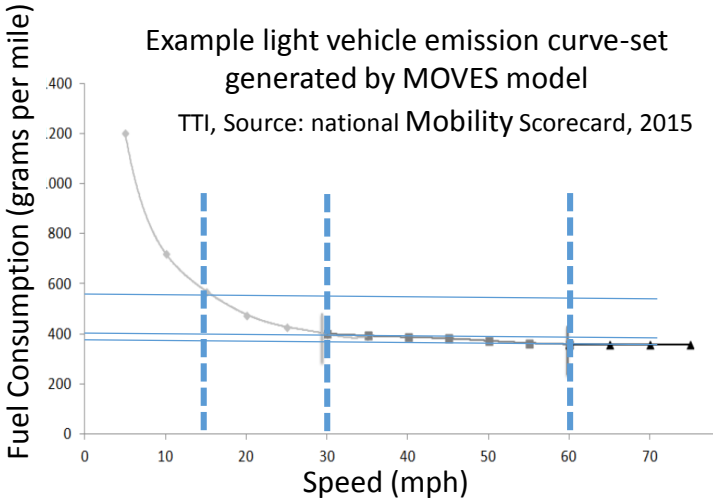
TECHNICAL ACCOMPLISHMENTS AND PROGRESS

1. Identified ~ 10 billion gallons of annual unproductive fuel consumption (by scenarios), in addition to the 3.1 billion gallon of wasted fuel reported in the National Mobility Scorecard
2. Identified opportunities for saving energy through Eco-Driving technologies
3. Reviewed a large set of existing work on Eco-Driving technologies and formulated a field-wide perspective on the status, estimation gaps, and research & development needs
4. Work in progress on collection of vehicle trajectory level data along a test corridor and at individual unsignalized intersection
5. Work in progress on Field Testing of EAD

Identify Gaps and Errors in National Mobility Scorecard (Task 1)

1. **No wasted fuel for speeds higher than 55 mph (estimation gap)**: At speeds greater than 55 mph, the tail end of the polynomial splines of the MOVES model remain constant using 30-60 mph emission values
2. **Not factoring in unnecessary stops at unsignalized intersections (estimation gap)**: Factored no fuel consumption and emissions for traffic on local streets (14% of the total Vehicle Miles Traveled on 70% of the highway length)
3. **Not factoring in idling (estimation gap)**: 6 billion gallons of fuel (**https://www.anl.gov/es/reducing-vehicle-idling)
4. **Underestimated wasted fuel for stop-and-go in congested traffic (estimation error)**: approximate with averaged lower cruising speed
5. **Underestimated wasted fuel for stops in front of traffic signals (estimation error)**: approximate stop trajectory with average lower speed



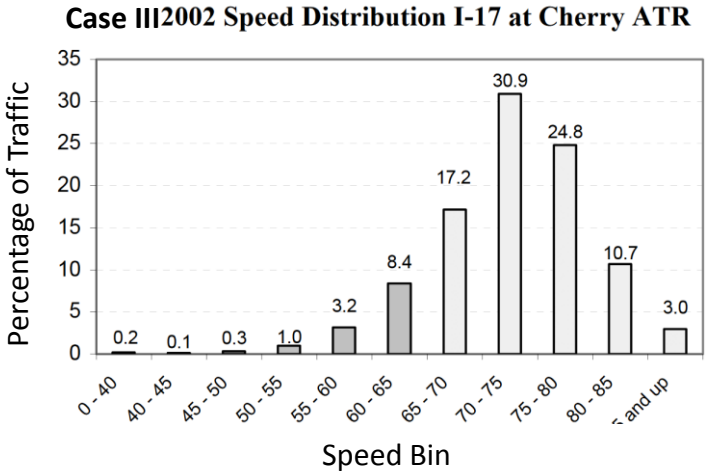


How much unproductive fuel is consumed in additional to the reported 3.1 billion gallon?

Analysis of Unproductive Fuel Consumptions –
Estimation of Wasted fuel for Speeds Higher Than 65 mph

Assumptions

- 40% of all trips occur during off-peak
- 30-60% of the average trip length take place on freeways
- The distribution of speed on freeway follows left skewed distribution, 5 example speed distribution examples in Arizona are used to generate unproductive fuel consumption estimates



Sherry L. Skszek, Actual Speeds on the Roads Compared to the Posted Limits, ADOT Report #551, October 2004

Estimation of unproductive fuel consumption (Million Gallons）

		Case I	Case II	Case III	Case IV	Case V	Averaged unproductive Fuel Consumption
% of vehicles exceed 65 mph		24%	25%	87%	93%	93%	
% of highway driving/trip	30%	426,122	472,822	1,690,085	2,207,571	2,088,565	1,377,033
	60%	1,019,841	1,073,379	4,533,566	5,059,635	5,192,898	3,375,864

Driving beyond 65 mph can on the average result in 1-3 billion gallons of unproductive fuel consumptions

Analysis of Unproductive Fuel Consumptions - Necessary Stops at Unsignalized Intersections

- ‘Unnecessary’ stops: Vehicles come to a stop at a stop sign in the absence of another vehicle or pedestrians at confronting approaches**

Time interval for a vehicle to clear the intersection

$$\tau = t_{stop} + t_{clearance}$$

Probability of *n* vehicles arrive within the time interval τ

$$p(n) = \frac{(qt)^n}{n!} e^{-q\tau}$$

Probability of two or more vehicles arriving at the time window τ

$$p(n \geq 2) = 1 - \left(p(0) + p(1)\right) = 1 - (1 + qt)e^{q\tau}$$

Table: Defining unnecessary stops

Flow (veh/hr)	100	200	300	400	500	600	700	800
7sec Interval	2%	6%	12%	18%	25%	33%	39%	46%
5 sec interval	1%	3%	7%	11%	15%	20%	25%	31%

< 30% of chance for more than one vehicle to arrive at a stop sign controlled intersection one after another within 5 to 7 sec interval (200ft-300ft@30mph)

** N. Zhang et al., Unsignalized Intersections: Can ITS Offer Improved Efficiency and Safety?, IEEE ITSC Conference, Washington DC, October 2011

Analysis of Unproductive Fuel Consumptions -
Unproductive Fuel Consumption at Stop Sign Controlled Intersections

Assumptions

- 2000 Average Daily Traffic (ADT) at unsignalized intersections (MUTCD* warrant on ADT volume for stop signs), heavy vehicles not considered
- ~ 10 grams of fuel is consumed per stop
- 20%-50% intersections are stop-sign controlled intersections

Estimation of unproductive fuel consumption

% of intersections with stop signs	20%	30%	40%	50%
# of stop sign controlled intersections	1,221,521	1832282.1	2443042.8	3053803.5
# of stops at stop sign controlled intersections	891,710,622,000	1,337,565,933,000	1,783,421,244,000	2,229,276,555,000
# of unnecessary stops	624,197,435,400	936,296,153,100	1,248,394,870,800	1,560,493,588,500
Annual wasted fuel (gallon)	1,648,955,953	2,473,433,929	3,297,911,906	4,122,389,882

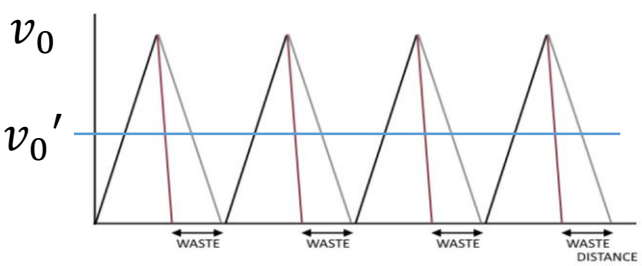
Unnecessary stops cause at least 2 to 3 billion gallons of unproductive fuel consumption

*MUTCD -Manual of Universal Traffic Control Device

Analysis of Unproductive Fuel Consumptions - Stop and Go in Freeway Congestion

The NMS estimation of fuel consumption of stop-and-go traffic in freeway congestion using lower average speed rather than accounting for acceleration and deceleration brings in errors

A MOVES case example (equivalent lower speed vs. stop and go)



v_0	Cruising at $v' = {}^{v_0}/_2$	Stop-and-go at $2m/s^2$
	Fuel (gallon/mi)	Fuel (gallon/mi)
10mph	0.15	0.16
15mph	0.10	0.12
20mph	0.07	0.10

Fuel consumption using lower average speed underestimates fuel consumption by ~10%

The difference between estimating power needs for traveling in stop-and-go(W_{sng}) traffic and at a lower cruise speed $v_0{}'$ ($W_{v_0{}'}$)

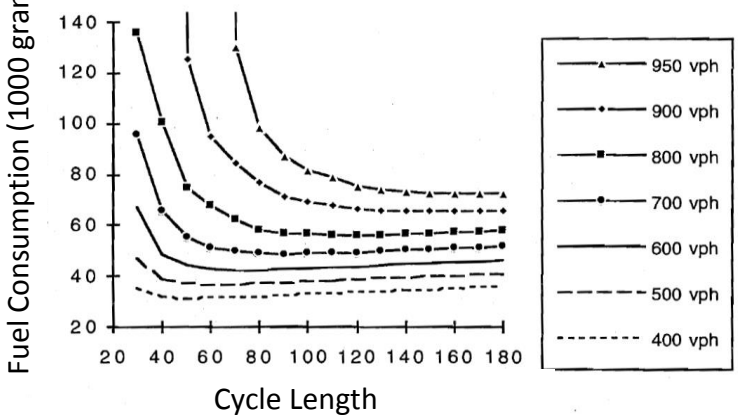
$$\Delta W = \frac{m \times v_0{}^2}{2D} + \frac{1}{4}\rho A T_0 v_0{}^3 - \frac{m \times v_0{}^2}{8D} + \frac{5}{64}\rho A T_0 v_0{}^3 = \frac{3}{8}\frac{m \times v_0{}^2}{D} + \frac{11}{64}\rho A T_0 v_0{}^3$$

Stop-and-go causes significant energy loss

Analysis of Unproductive Fuel Consumptions - Fuel Consumption at Signalized Intersections

- NMS estimates emissions and fuel consumption using averaged lower speeds. The idle operation such as waiting at a traffic signal, is not explicitly measured, but factored in 'the normal vehicle hours of operation' in MOVES
- The 'normal hours of vehicle operation' at signalized intersections is **not so normal**
  - As intersection approaches saturation, traffic queues add delays (idle) and additional fuel consumptions
  - Signal cycle time substantially impacts fuel consumption
  - Intersection designs introduce delays and additional fuel consumptions, e.g., dedicated left phase increase aggregated fuel consumption by 50%

Intersection fuel consumption with different signal cycle length



**Tsai-Yun Liao and Randy B. Machemehl, Fuel Consumption Estimation and Optimal Traffic Signal Timing, The Texas A&M University System Texas Transportation Institute, Research Report, Report # SWUTC/98/467312-1

Fuel consumption estimation using lower average speed to approximate traffic at signalized intersections may result in up to 50% errors

Summary -- 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 Scorecard

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 NMS estimated 3.1 billion gallons wasted fuel

**A trip decomposition analysis is being conducted to estimate the percentage of peak hour freeway trips involving stop and go, and subsequently to estimate the overall wasted fuel consumption for freeway congestions

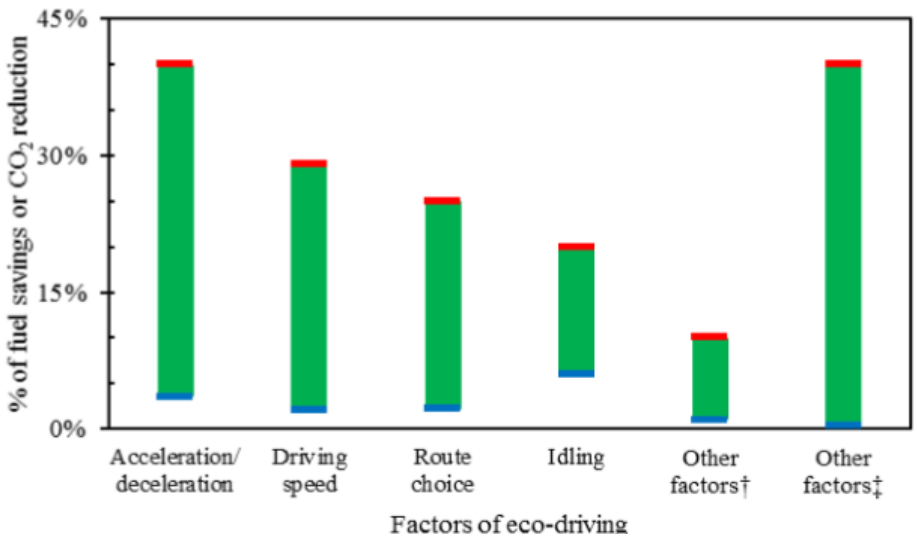
Assessment of Intelligent Transportaion Systems (ITS) Supported Eco-Driving Strategies (Task 1)

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 has been conducted 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

Assessment of ITS Supported Eco-Driving Strategies - Summary of Literature Review

Assessment

~200 papers were 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

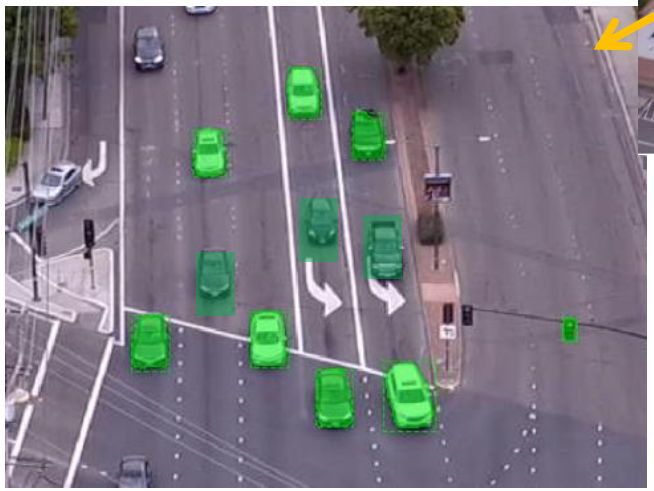
Urgent needs for studies of deployment issues

- Substantial field data under real-world conditions are needed
- Deployment issues, including policies, operation and safety need to be studied
- Safety of Eco-Driving needs to be evaluated in parallel to the technical development

Data Collection at Signalized Intersections/Corridor (Task 2 and Task 3)

Data collection

- A number of signalized intersections along a urban corridor
- Movement of vehicles movements, (w/classification), pedestrians and cyclists



Status

- Sample data have been collected
- AI-based image processing algorithm is being developed for extract traffic movements
- A full set of data are to be collected in June/July

Data Collection at Unsignalized Intersections (Task 2 and Task 3)

Data collection using 360º video camera

Observation

- Majority of vehicles stopping at stop signs do not encounter conflicting traffic
- 'Stop sign rollers' frequently occur
- 360 video camera can be used to detect and track vehicles at smaller intersections

Status

- Data were collected at two intersections
- AI-based image processing algorithm has been developed
- More data will be collected in May/June

Field Testing of EAD (Task 4)

An Eco Approach and Departure prototype system is being prepared:

- **A fully instrumented test vehicle to acquire vehicle movement as well as surrounding activities**
- **V2I to receive SPaT messages**
- **HMI to inform a driver of permissive time window or ETA to red**

Collect data on movement of the subject vehicle, the movements of surrounding vehicles, and the traffic along the corridor

Evaluate fuel consumption savings of the subject vehicle due to Eco-Driving and its impacts to the surrounding traffic

Responses to Previous Year Reviewer's Comments

A reviewer noted that the original project was composed of tasks that did not align well

- **Response: We worked with VTO to divide the project into two distinct projects.**

A reviewer was not sure that given the level of funding, there is much expected from the experimental evaluation of eco-driving strategies.

- **Response: After re-scoping the project, additional funding was provided by DOE which will help ensure the project's goals can be achieved.**

COLLABORATIONS WITH OTHER INSTITUTIONS

- The project team has been in communication with other project teams to understand their needs for the field data
  - Working with the CAV lead Eric Rask of Argonne National Lab (ANL) for project scope update and technical exchange
  - Plan to work with ANL team to apply Autonomie for estimating fuel consumption using the field data and provide feedback on model use experience
  - Discussed with ANL for needs on field data
- Collaborate with Professor Jacob Tsao of San Jose State University on trip decomposition analysis
- The collected data, models and analyses from this study will become inputs to the simulation studies under the SMART Mobility program

Remaining Challenges and Barriers

- Realistic operation scenarios, including a full range of operation conditions, as well as the benefits and impacts on efficiency and safety at the system level must be considered
- Deployment issues including technological, operation, safety and institutional barriers must be addressed
- Field data is essential for problem understanding and verification of the solutions
- The contract process for the cost-share UCB project has been delayed. Consequently, the planned installation of radars along the CA Connected Vehicle corridor can not be accomplished within the duration of project. The project team has developed an alternative solution to collect data (using an aerial drone)

PROPOSED FUTURE RESEARCH

Studies of deployment issues for Eco Driving

Built upon the analyses conducted under the current project, the proposed scope includes the following three aspects:

1. **In-depth study of deployment issues to address technical, operation and implementation aspects of Eco-Driving technologies and strategies**
2. **Study of innovative Eco-Driving concepts for mitigating unproductive fuel consumptions due to the major scenarios identified under this study (i.e., speed higher than 65mph, unnecessary stops at unsignalized intersections, stop-and-go on highways, Eco Approach and Departure and idling -- w/ combined unproductive fuel consumption of 10 billion gallons)**
3. **Collect field data to extend and support the analyses on unproductive fuel consumptions and benefits of Eco Driving strategies/technologies**

Any proposed future work is subject to change based on funding levels

CONCLUDING REMARKS

- ~ 10 billion gallons of annual unproductive fuel consumption is identified, in addition to the 3.1 billion gallon of wasted fuel reported in the National Mobility Scorecard, categorized in four operation scenarios: travel at speeds higher than 65 mph, unnecessary stops at unsignalized intersections, stop-and-go driving in congestion, and stops-at-signal
- Studies-to-date on ITS supported Eco-Driving technologies are at the exploratory stage, many with optimistic benefit estimates, lack of supporting test data and realistic deployment considerations
- To be collected real world field data will support analyses of unproductive fuel consumptions in urban areas -- at signalized and unsignalized intersections
- The planned experimental evaluation of Eco Approach and Departure will provide scientific evidence of the benefits of EDA as well as the impacts to surrounding traffic
- The work conducted under this project for quantification of unproductive fuel consumption and identification of the opportunities for Eco Driving is an important step toward a systematic 'Eco Driving strategy'

NEXT STEPS

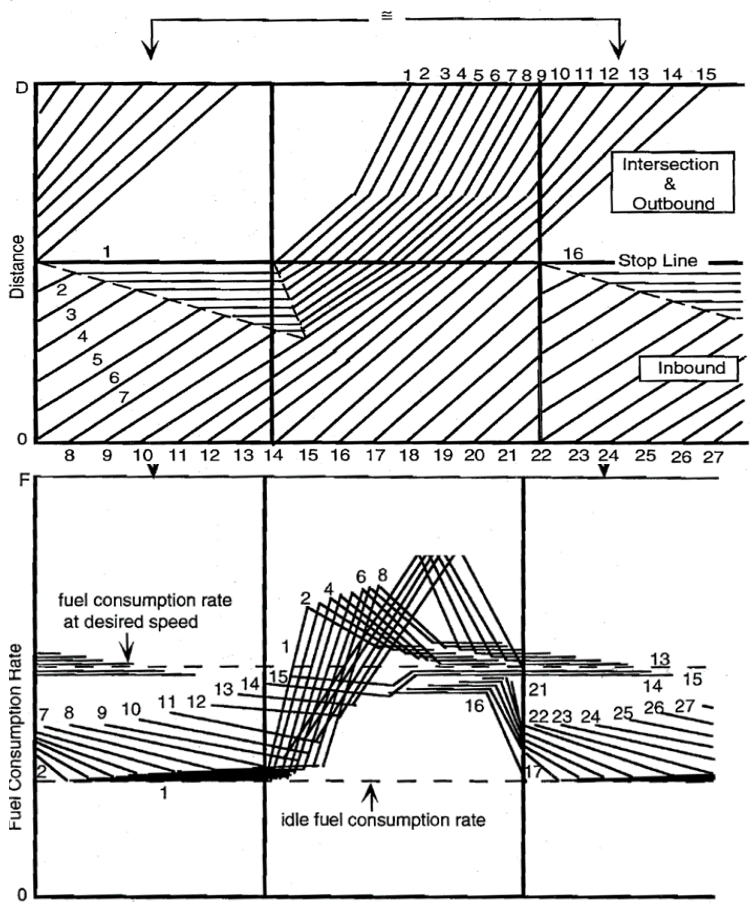
- Complete the analysis of unproductive fuel consumptions through trip decomposition
- Collect vehicle trajectory level data at a signalized arterial corridor and analyze the data to estimate fuel consumptions at vehicle and intersection levels
- Collect vehicles and pedestrians movement data at unsignalized intersections and analyze the operation, fuel consumptions, and safety of unsignalized intersections
- Test a Eco Approach and Departure prototype system to evaluate fuel saving benefits to the subject vehicle and impacts to surrounding traffic
- Complete project final report

QUESTIONS?

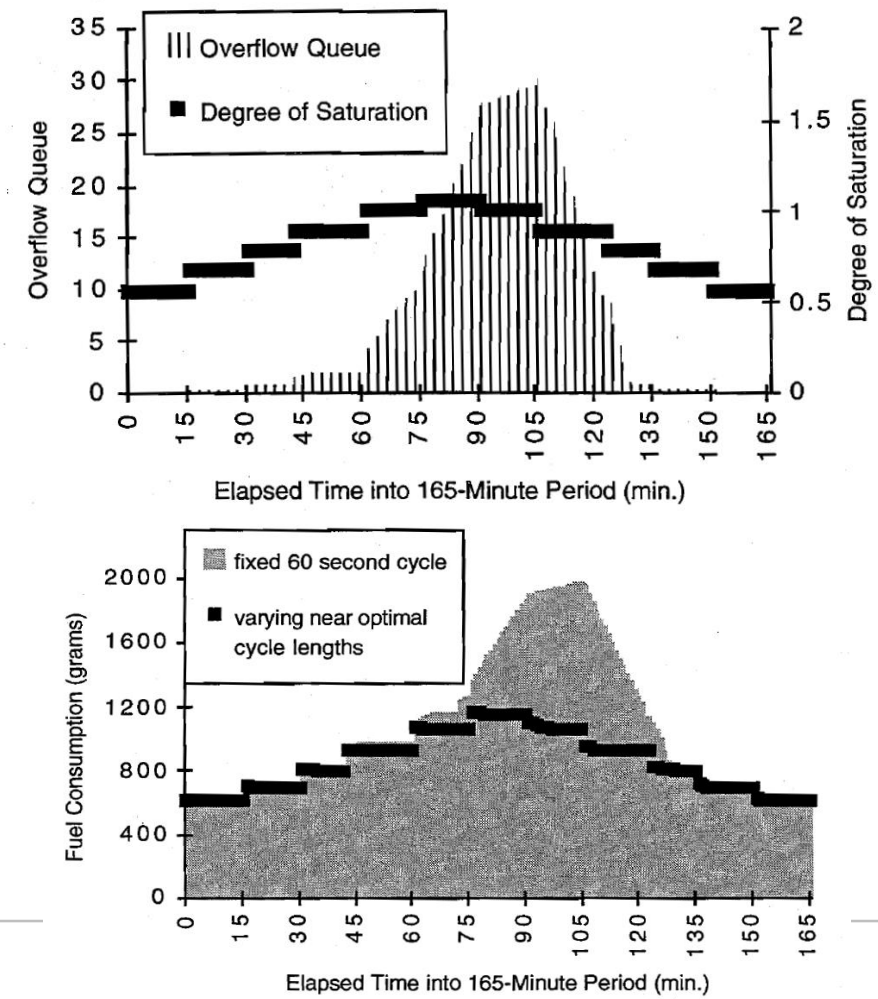
TECHNICAL BACK-UP SLIDES

Fuel Consumption at Signalized Intersections

Vehicle trajectories and fuel consumptions when crossing an intersection**



Saturation degree and fuel consumptions



**Tsai-Yun Liao and Randy B. Machemehl, Fuel Consumption Estimation and Optimal Traffic Signal Timing, The Texas A&M University System Texas Transportation Institute, Research Report # SWUTC/98/467312-1

Trip Decomposition Analysis **

- Further analyses are being conducted to conduct trip decomposition in order to fine tune the unproductive fuel estimates and to identify how Eco-Driving Technologies/strategies can address these unproductive fuel consumptions
- Decision Variables: x_{PRADH}
  - P - Purpose type: commute, shopping, other family/personal errands, social/recreation, others.
  - R - Roadway Type: freeway, arterial, collector
  - A - Area type: urban vs. rural
  - D - Day type: weekday vs. weekend day
  - H – Hour: specific hour of a day (or period consisting of consecutive hours)
- Objective Function:

$$\text{Maximize } -\sum_P \sum_R \sum_A \sum_D \sum_H x_{PRADH}\, Ln\, x_{PRADH}$$

- Constraint Types:

$$\sum_P \sum_R \sum_A \sum_D \sum_H x_{PRADH} = \text{Total VMT}; \quad \sum_R \sum_A \sum_D \sum_H x_{PRADH} = \text{VMT}_P \text{, for all P}$$

$$\sum_R \sum_A \sum_D x_{PRADH} = \text{VMT of P \& in H} = (\text{\# of P trips}) \times (\text{ave. length of P trips}) \times (\text{\% of P trips in H})$$

** This task is being conducted by Prof. Jacob Tsao of San Jose State University

Technology Review Example: Eco-Approach and Departure

- **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
- **Further research needs**
  - Robust EAD systems to handle inaccurate signal timing prediction and consecutive signals
  - The distraction issues need to be addressed
  - The impact of 'EAD driving behavior' to other vehicles
  - V2I supported CACC

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

Technology Review Example: Platooning

- Knowledge gained
  - High accuracy spacing or headway regulation are achieved through V2V supported vehicle control
  - Fuel savings achieved at highway speeds. Increased fuel savings when gaps between vehicle are small and combined with existing air resistance reduction products (e.g., side skirts)
- Further research needs
  - Evaluation of realistic fuel benefits for real-world operation scenarios, e.g., at an array of speeds, platooning forming, and impacts to other traffic
  - Evaluation of safety of platooning under hazardous conditions and countermeasures
- Deployment:
  - Truck CACC products are under testing and refinement (e.g., Peloton)

Authors /Ref.	Test veh/site	Test settings	Fuel savings
Michaelian et al. (2000)	2-4 trucks, HOV lane on I-15, California	3-6m gap, @ 60mph	3-4% (lead) 10% (mid) 7% (trail)
Browand et al. (2004)	2 trucks, taxiway@ Crows Landing	3-10m gap, @50-55 mph	5-10% (lead) 10-12% (trail)
Bonnet & Fritz (2000)	2 trucks, Papenburg, Germany	5-16m gap, @ 37-50mph	3-10% (lead) 10-21% (trail)
Tsugawa et al. (2014)	3 trucks, test Track and closed Expressway, Japan	4.7-20m gap, @ 50mph	9-16%
Bishop et al. (2017)	2 trucks, TRC test track, Ohio	9-46m gap, @ 65mph	4.5-7.0%
Shladover et al. (2018)	3 trucks, I-710 corridor, California	0.6 sec (17m), 1.5 sec (43m) gap, @ 65 mph	~0% (lead) 7-6% (2nd) 11-9%(3rd)

Estimating Unproductive Fuel Consumptions

Assessment of Eco-Driving Technologies/Strategies