Automated Transportation: IMPLICATIONS FOR ADVANCED VEHICLE ENERGY TECHNOLOGIES

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Grand Challenge: Spatial Mismatch in Resources and Demand

Where we have
Where we live

Can Transportation Overcome it?

- Maps from National Renewable Energy Laboratory (NREL)
Road Terrain Preview Increases Energy Efficiency of Hybrid Vehicles

**Motivation:** Utilize road terrain preview to predictively plan use of the battery and reduce energy use in hybrid vehicles.

- In hybrid vehicles, the energy buffer provided by the battery, allows running a smaller engine more efficiently and capturing regeneration energy.

- The added efficiency depends strongly on the energy management strategy.

- Uncertainty about future power demands is the main bottleneck to making "optimal" energy management decisions.

**Results:** Knowledge of upcoming hills can enhance energy efficiency of hybrids particularly at low speeds and when the elevation change is large.

**Motivation:** Blended use of engine and battery results in the best energy efficiency but requires knowledge of trip distance and future power demands.

- Connectivity can help in learning trip patterns and therefore may provide information about the distance to next charging station and expected power demands along the way.
- Information such as traffic conditions, speed limits, road terrain profile can all be helpful in better estimating future power demands.

**Results:** We have data from driving on hilly roads that we use for simulation of a plug-in hybrid vehicle.

<table>
<thead>
<tr>
<th>Information Level</th>
<th>Route 1 Uphill and Downhill</th>
<th>Route 2 Uphill</th>
<th>Route 3 Downhill</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Preview</td>
<td>No Preview: 5 to 17% lower than optimal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trip Distance, Terrain</td>
<td>Partial Preview: 1 to 7% lower than optimal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trip Distance, Terrain, Speed Limits</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Eco-Driving Enabled by Vehicle to Infrastructure Communication

**Motivation:** Improve energy efficiency via communication between connected vehicles and infrastructure

**Example:** Reducing Idling at Red Lights Saves Fuel: A constrained optimal control problem

**Results:** Monte-Carlo simulations of many drives on many streets with widely varying signal timings.

<table>
<thead>
<tr>
<th></th>
<th>Mean MPG</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Information</td>
<td>23.5 MPG</td>
</tr>
<tr>
<td>Real-Time Info</td>
<td>26.9 MPG</td>
</tr>
<tr>
<td>(with probabilistic models)</td>
<td></td>
</tr>
<tr>
<td>Full Information</td>
<td>30.1 MPG</td>
</tr>
</tbody>
</table>


Intelligence improves efficiency and mobility

Online Energy Tracking
The probability of completing the mission successfully with the remaining energy is tracked by combining prior knowledge about mission with real-time data.

Battery Power Management
Using a thermo-electric model, the maximum battery power is controlled to avoid violation of voltage, temperature, and SOC limits.

Energy Efficient Coverage Planning
The velocity profile along the path is optimized to minimize energy consumption, avoid inefficient motor operation, and maximize coverage.

Locomotion Power Estimation
Terramechanics models are utilized to predict the power needed for locomotion on a given terrain type depending on velocity and turning radius.

Better energy intelligence: potential for improved energy efficiency and mobility


Operating within Power Limits
Optimal Power Management

Optimal control problem

\[
\min_{u_k} \left\{ \sum_{k=0}^{N-1} \alpha F C_{\text{norm}} + \beta BS_{\text{norm}} + \gamma |I_{\text{norm}}| \right\} 
\]

Fuel consumption \hspace{1cm} Cumulative Bulk stress

SOC range \hspace{0.5cm} -0.2 \leq SOC_k - SOC_0 \leq 0.2

SOC sustainability \hspace{0.5cm} SOC_0 = SOC_N

Battery power limit \hspace{0.5cm} -20 \leq u_k \leq 20

Generator power limit \hspace{0.5cm} 0 \leq P_{g,k} \leq 58

Generator power rate limit \hspace{0.5cm} -11 \leq \Delta P_{g,k} \leq 11

State \hspace{0.5cm} x_k = \left[ \begin{array}{c} SOC_k \\ P_{g,k} \end{array} \right]^T

Control (battery power) \hspace{0.5cm} u_k = P_{b,k}

Vehicle power demand \hspace{0.5cm} w_k = P_{d,k}
Look-ahead control
ZEVs are the no-compromise alternative to fossil fuel combustion.

*every new car sold in 2040 and beyond will need to be a ZEV*
In Aug 2012, the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) announced the final standard governing new-vehicle fuel economy for model years 2017 through 2025.
A glance around the Globe

Fuel Economy Targets

Figure: An, F. and A. Sauer; 2004 Comparison of Passenger Vehicle Fuel Economy and GHG Emission Standards around the World, ICCT
History Lessons
Slow? Slender? No, just better!
Enabling Actors Behind-the-Scenes

And some of the real Actors

Jessy’s Air Charge Estimator
Ilya @ Ford
Anna’s PhD
Mrdjan’s diVCT

Fuel Delivery
<table>
<thead>
<tr>
<th>Valve Timing</th>
<th>Number of Valves</th>
<th>Key</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbureted</td>
<td>Fixed</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Variable</td>
<td>2</td>
</tr>
<tr>
<td>Throttle Body Injection</td>
<td>Fixed</td>
<td>3</td>
</tr>
<tr>
<td>Port Fuel Injection</td>
<td>Fixed</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Variable</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Multi-Valve</td>
<td>6</td>
</tr>
<tr>
<td>Gasoline Direct Injection (GDI)</td>
<td>Fixed</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Multi-Valve</td>
<td>8</td>
</tr>
<tr>
<td>Diesel</td>
<td>—</td>
<td>9</td>
</tr>
</tbody>
</table>

Carburetor
Throttle Body Inj
Multi-Valve
Variable Valve
Port Fuel Injection

Fuel Consumption/HP (gall/100 mi)/HP

Port Fuel Injection
Variable Valve Timing

Model Year
Gasoline versus Diesel

Gasoline

- Spark Ignition "Gasoline engine"
  - Spark ignites premixed fuel + air
  - Propagating flame

- Hot Flame Region: NOx

- Electronic Throttle
- Variable Valve-train (Timing & Lift)

Stoich TC–DI–VVT–VVL–SI

Diesel

- Compression Ignition "Diesel engine"
  - Fuel injected into compressed air
  - Diffusion flame

- Hot Flame Region: NOx & Soot

- Turbo-Charging
- Direct-injection

Spark Ignition (SI)

Compression Ignition (CI)

Gasoline Efficiency Improvement

- Ford, with its Ecoboost turbocharging technology, makes a small engine act big.
- GM, with its Active Fuel Management cylinder deactivation system, makes a big engine act small.

*R. Truett, Auto News, Jan 6, 2014*
Efficiency Improvement

What next?

The next frontier is Lean Combustion

Fantastic!!

Controlling the Dynamics

1. Dnsz
2. TC-Dnsz
3. vTC
4. eTC
5. Cnv
6. preview

Market Share of Gasoline Turbo Vehicles

Original SI NA 3.6L V6

Downsizing

Turbocharged SI 2.0L I4
To ignite its charge, Controlled AutoIgnition relies on elevated-temperature homogeneous charge instead of stratification (in-homogeneities).

Also known as:
- Homogeneous Charge Compression Ignition (HCCI)
- DiesOtto
**Challenge:**
Ignition cannot be actuated directly. Controlled through thermal management of charge (dilution)

<table>
<thead>
<tr>
<th></th>
<th>SI</th>
<th>HCCI</th>
<th>CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Temperature (K)</td>
<td>&gt;2000</td>
<td>1600</td>
<td>1700</td>
</tr>
<tr>
<td>NOx emission</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Combustion Duration (CAD)</td>
<td>15-40</td>
<td>2-10</td>
<td>40</td>
</tr>
<tr>
<td>Burn Rate (J/CAD)</td>
<td>70</td>
<td>120</td>
<td>110</td>
</tr>
<tr>
<td>Pressure Gradient (bar/CAD)</td>
<td>0.5-2</td>
<td>2-16</td>
<td>&gt;4</td>
</tr>
</tbody>
</table>
HCCI Efficiency Benefits?

Original SI NA 3.6L V6

Downsizing

Turbocharged SI 2.0L I4

BSFC V6 [g/kWh]

BSFC Improv. V6–I4 [%]

Fuel economy (mpg)

24.1%

22.0%
HCCI Load Control Experimental Results

Significant number of mode transitions during driving cycle!
Mode Transitions

2014, Nüesch et al., Mode Switches among SI, SACI, and HCCI Combustion and their Influence in Drive Cycle Fuel Economy, ACC, accepted
Multiple Fuel Injections
Mixing the Perfect Fuel

The New Frontier

Ethanol

Natural Gas
Energy-Lean Information-Rich Transportation

Electrical Grid

Gas Grid

Transportation Grid

Information Grid

National Highway System

Legend
- Interstate Pipelines
- Intrastate Pipelines

Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Gas Transportation Information System
Vehicle supported microgrids

Optimal scheduling of power flow

Inverter-based regulation of microgrid frequency and voltage

Optimal sizing of components

28% savings in annual fuel consumption due to an integrated optimal design


Coupled infrastructures

Tighter coupling of infrastructures: potential for improved penetration of renewables
Can we shift the energy map?
Thanks to

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William Lim, Kathie Wolney, Charlotte Bowens (ARC) ....
Ilan Gur, Ken Howden (DOE)
Coupled infrastructures

Resilient Municipality: Ann Arbor, Michigan

[Diagram showing various infrastructure elements like electrical grid, natural gas, coupled facilities, and transportation systems.]

Local Carriers

Landfill Gas Recovery

Hydro

Solar

Wind

E → H₂

NG Storage

Residential Hub

UMICH CPP

Campus Hub

Colleges
Dorms
Labs

Commercial Hub

Commuter Bus
(CNGV,PHEV,BEV)

CHP

FCV

PHEVs