CONNECTED AND AUTOMATED VEHICLES AND ADVANCES IN POWERTRAIN CONTROL TO ACHIEVE IMPROVED FUEL ECONOMY

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June 23rd 2016
I am grateful to Brian Rahman, PhD student, and Leo Bauer, MS student, for their assistance in the preparation of these slides.
“Tomorrow’s university will be different than today’s. Only those who thrive in multiple dimensions, not just research or traditional education, will succeed.”

-Giorgio Rizzoni
CAR Director
CREATING THE ENVIRONMENT

- Experiential Learning
- Experimental Vehicle Projects
- Engineering Services
- Federally Funded Research
- Industry Consortia
- Proprietary Industry Research Projects
- Spin Off Companies
CAR provides experiential learning opportunities to over 250 undergraduate and graduate students each academic year.

In line with the *College of Engineering’s strategic objective* to “build on our strength in experiential learning to establish national leadership in this area for Ohio State”
In partnership with the academic departments, CAR contributes to and continuously improves a graduate curriculum with focus on automotive systems engineering, taught by CAR-affiliated faculty.

This is in line with the College of Engineering’s goal to “produce graduates with advanced degrees who become national and international leaders in their field.”
SNAPSHOT OF CAR – FY 2015

Personnel

In the 2014-2015 academic year, there were a total of 273 associates:

- **46** Visiting Scholars/Other
- **26** Research Staff
- **50** Student Assistants
- **10** CAR fellows
- **29** CAR-Affiliated Faculty
- **9** CAR-Affiliated Faculty
- **9** Research Support Staff
- **80** Graduate Students
- **14** Administrative and Business Development Staff

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CENTER FOR AUTOMOTIVE RESEARCH
CONNECTED AND AUTOMATED VEHICLES AND ADVANCES IN POWERTRAIN CONTROL TO ACHIEVE IMPROVED FUEL ECONOMY
1. Motivation

2. Eco-Driving, Eco-Routing

3. An example: Cloud-based Velocity Profile Optimization

4. What can be done under the hood (powertrain and accessories)?

5. How can recent advances in connected and automated vehicles be integrated into powertrain control?
• Two important technology trends have developed in recent years in the passenger and commercial vehicle industries:
  i. the push towards significantly reduced CO₂ emissions and improved fuel economy (FE)
  ii. the development and introduction into the market of connected and automated vehicle (CAV) technologies.

• The aim of this talk is to:
  i. review recent research advances in leveraging CAV technologies to enhance vehicle FE
  ii. to explore opportunities that will enable closer integration of CAV technologies with powertrain control to further extract the maximum benefit that can be achieved by the merger of vehicle connectivity and automation with powertrain control.

• The presentation outlines how vehicle engine, transmission, hybrid powertrain, and accessory management can benefit from vehicle-level information (local range sensors, navigation systems, V2X communications), system level information (traffic, geography, weather and road conditions), and cloud level processing.

The merger of these two rich areas of research and development will continue to provide rich opportunities for our research community, and is especially relevant to this Symposium.
MOTIVATION
Figure 2: Total energy supply by energy commodity 1971 – 2013, TWh

- Windpower
- Hydropower
- Primary heat
- Nuclear fuel
- Other fuels
- Natural gas, gasworks gas
- Crude oil and petroleum products
- Coal and coke
- Biomass

Swedish Energy Agency, 2015
What I know about Sweden, I think, offers us some good lessons. Number one, the work you have done on energy I think is something the United States can and will learn from. Because every country in the world right now has to recognize if we are going to continue to grow and improve our standard of living while maintaining a sustainable planet, we are going to have to change our patterns of energy use. And Sweden I think is far ahead of many other countries.

Barack Obama, 2013
World Energy Portfolio: 2010 and 2040 projections

- Global Primary Energy grows by 36% (vs. population growth of 25%)
- High annual growth rate of renewables (solar, wind and biofuels) but share remains insignificant (<3% share in 2040)
- Oil, gas and coal continue to dominate (77% share in 2040)
- Increase in oil, gas and nuclear EACH exceeds 2040 share of renewables!!

Exxon Mobil 2013 World Energy Outlook | http://www.slideshare.net/MarcellusDN/exxonmobil-2013-the-outlook-for-energy-a-view-to-2040 | (DOE projections are similar)
Transportation is 96% dependent on petroleum
Proven reserves continue to increase

Source: EIA, 2015

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<td>2016</td>
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<td>137000</td>
<td>117000</td>
</tr>
</tbody>
</table>
PETROLEUM…IS INEXPENSIVE!

U.S. Gasoline and Crude Oil Prices

- Price difference
- Retail regular gasoline
- Crude oil

Crude oil price is composite refiner acquisition cost. Retail prices include state and federal taxes.

Source: Short-Term Energy Outlook, March 2015.
PETROLEUM...IS A SIGNIFICANT CONTRIBUTOR TO GREENHOUSE GASES

- Regulations worldwide aim to reduce CO₂ emissions from transportation
- How do we reconcile this with inexpensive petroleum?
US PETROLEUM USE RECENT HISTORY

Domestic Oil Production and Imported Petroleum (million BPD)
Source: EIA

- Total Oil Use
- Imported Oil
- Total Gasoline Use
- Domestic Production
- Total Middle Distillate Use
GOAL

Domestic Oil Production and Imported Petroleum (million BPD)
Source: EIA

- Total Oil Use
- Imported Oil
- Total Gasoline Use
- Domestic Production
- Total Middle Distillate Use
ARPA-E issues $30M NEXTCAR program funding opportunity; 20% reduction in energy consumption beyond current regulatory requirements
ECO-DRIVING
ECO-DRIVING

- Eco-driving is the ability to save fuel and limit emissions based on the driving behavior
  - Ability to apply to any vehicle as it does not require any modification to powertrain

- First developed as lessons to change driver behavior at the wheel to provide greater fuel efficiency

- Main idea is to smooth drive cycle, avoid unnecessary braking or acceleration, anticipate traffic, etc.

- Goal is to try to maximize vehicle fuel efficiency with only driver input

- Fuel economy observed of up to 20% compared to aggressive driving [1]

- However approaches have been made to assist driver to achieve even better fuel economy, biggest improvements have come from cruise control technologies especially in highway scenarios

• Advances in software and computation now allow for more systematic approach to eco-driving

• Mainly two types of approach
  • **Pre-trip systems**
    • Makes use of on-board navigation systems and input determined before the drive
  • **In-trip systems**
    • Live feedback provides ability of Advanced Driver Assistance Systems
    • Made possible through the improvement of on-board computation capabilities, as well as connectivity to cloud-based servers

• Advances in eco-driving control strategies
  • Real time computing of optimal velocity profile, paired to parametric optimization of the engine [2]
  • Eco-cruise control using predictive logic [3]
  • Right now very useful for highway and extra-urban setting to provide improve the Adaptive Cruise Control

Rahka, Overview of VTTI’s Environmental Connected Vehicle Research Activities [3]
Eco-routing is the identification of the most fuel efficient route for a vehicle travelling between two points.

Pre-trip systems can determine at the time of travel which route will be the most fuel efficient given current data at the time of calculation.

However, new projects using advanced computation have been able to improve such eco-routing to adapt it to current conditions.

- By combining recorded data to real-time traffic conditions, and algorithms that provide the shortest path to the most fuel efficient route; it’s been observed fuel savings of up to 14% [4].

Combining optimal route with assisted, and eventually automated, eco-control strategies have potential to work well together to increase fuel economy.
AN EXAMPLE: CLOUD BASED VELOCITY PROFILE OPTIMIZATION

Rx Package

OSU GIS Server

OSU Optimization Server

Google

Tx Package

Text files define driver input

Auto with:
Laptop
Small Display
GPS Receiver
CAN-to-USB Conv.
4G Capable Int. Con.
Objective:
Move the vehicle from position A to B minimizing fuel consumption over the trip.

Process:
Build a velocity profile based upon the GIS, online traffic, speed limits, traffic light timings, stop sign information stored in large databases.

To find the optimal solution to move the vehicle from position A to B, a vehicle simulator on the cloud side is used to solve a dynamic programming problem which uses all the traffic and GIS information problem.
OPTIMIZATION PROBLEM FORMULATION

- **State:** velocity \( (v) \)  \[ \dot{v} = f(v, F_{trac}) \]
- **Independent variable:** distance \( (D) \)

- **Performance Index:**
  \[ \min_{u \in U} \int_0^{D_f} m_f (T_{ice}, \omega_{ice}) dD \]

- **Control input:** Engine torque \[ T_{ice_{-}min} \rightarrow T_{ice} \rightarrow T_{ice_{-}max} \]

- **Constraints:**
  \[ v(0) = 0; v(D_f) = 0 \]  \[ \text{Boundary conditions} \]

  \[ \frac{dv}{dD}_{min} < \frac{dv}{dD} < \frac{dv}{dD}_{max} \]

  \[ 0 < v < v_{max}(D) \]

Where \( D_f \) is the length of the trip (distance from A to B) Maxmum velocity is function of distance, it changes according to the location of intersection, stop sign, traffic flow etc.
1. Routing Data
2. Road Grade
3. Traffic Information
   - Speed Limits
   - Statistical Average Speed
   - Measured Average Speed
   - Stop Signs
   - Traffic Light Timing

Legend:
ArcGIS Server
Google Maps API
Navteq, Historical Traffic Model,
Local Transportation Departments

Auto with:
Laptop
Small Display
GPS Receiver
CAN-to-USB Conv.
4G Capable Int. Con.

Text files define driver input

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TEST VEHICLE

Fully Equipped Test Vehicle

- Lincoln MKS provided by Ford.
- GPS Receiver
- CAN-to-USB Converter
- 4G Capable USB Modem
- Screen
- Laptop

Continuously Receives Data from ECU and GPS (Data Fusion)

Communication with Server

- Capable of sending information to server
- Receives optimal velocity profile

Continuous Position Synchronization

- Accurately shows advised velocity at correct position.

### Highway Route Example

**Route Type**: Highway

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<tr>
<th>Total Distance</th>
<th>25 miles</th>
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<table>
<thead>
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<th>Route Type</th>
<th>Total Fuel Consumption [gal]</th>
<th>Fuel Economy Improvement [%]</th>
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<td>Natural Driving June 8th</td>
<td>1.036</td>
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<tr>
<td>Advisor Following June 8th</td>
<td>0.9024</td>
<td><strong>12.9</strong></td>
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<tr>
<td>Advisor Following July 6th</td>
<td>0.884</td>
<td><strong>14.7</strong></td>
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<tr>
<td>Average Fuel Economy Improvement</td>
<td></td>
<td><strong>13.8</strong></td>
</tr>
</tbody>
</table>

(Compared to actual baseline of test June 8th)
Baseline Velocity Profile (Test of June 8, **Driver**: E. Ozatay, # of Passengers = 2)
Advisory Velocity Profile (Test of June 8, **Driver:** E. Ozatay, # of Passengers = 2)
Advisory Velocity Profile (Test of July 6, **Driver**: J. Michelini, # of Passengers = 2):
## TEST RESULTS COMPARISON

<table>
<thead>
<tr>
<th></th>
<th>Total Fuel Consumption [gal]</th>
<th>Fuel Economy Improvement [%]</th>
</tr>
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<tbody>
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<td>13.8</td>
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(Compared to actual baseline of test June 8<sup>th</sup>)
Dearborn short route

- 5.4 miles
- Urban, freeway combined route
- 8 different drivers performed 2 sets of tests
  - Natural driving
  - Advisor following
- Tests performed with 2 passengers
TEST RESULTS

Test-1 Velocity Profiles

Driver: John

- Advised Speed
- Natural Driving
- Advisor Following

Velocity [mph] vs. Distance [miles]
Test-2 Velocity Profiles

Test Results
Test-3 Velocity Profiles

Driver: Diana

- Advised Speed
- Natural Driving
- Advisor Following
Test-4 Velocity Profiles

Driver: Vladimir

- Advised Speed
- Natural Driving
- Advisor Following

Velocity [mph]

Distance [miles]
Test-5 Velocity Profiles
Test-6 Velocity Profiles
Test-7 Velocity Profiles
## TEST RESULTS (URBAN DRIVING)

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<td>19.9</td>
<td>9.7</td>
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LET’S GO UNDER THE HOOD...
Further Development of Existing Technology

- Ultra-lean operation from advanced boosting, fueling, and ignition systems
- Control of auxiliary load timing
- Dilution through air or EGR
- Variable compression ratio engines
- Very high compression with knock mitigation
- Low temperature combustion, dual fuel or reactivity controlled combustion

http://arpa-e.energy.gov/sites/default/files/02_Atkinson_Powertrain_Innovations.pdf
Further Development of Existing Technology, cont.

- Friction, pumping loss, and auxiliary load reduction
- Thermal loss reductions (reduced surface area available for heat transfer)
- Automatic engine stop/start
- Waste heat and direct energy recovery systems
- Hybridization (eAssist, start/stop, regenerative braking, engine transient management, ...)

http://arpa-e.energy.gov/sites/default/files/02_Atkinson_Powertrain_Innovations.pdf

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New engine architectures

- **Free piston** engines
- **Split-cycle** engines
- Entirely **new** thermodynamic and combustion **cycles**

New engines and powertrain operating systems

- **Variable displacement** engines
- **Intermittent operation** engines
- **Integration** with electric machines or other **hybrid systems**

http://arpa-e.energy.gov/sites/default/files/02_Atkinson_Powertrain_Innovations.pdf
HOW CAN ADVANCES IN CONNECTED AND AUTOMATED VEHICLE TECHNOLOGY BE LEVERAGED?
• Advances in CAV technology enable information on destination, terrain, traffic signals, weather, other vehicles, etc. to be readily available at the individual car level.

• How can advancements in CAV technology be leveraged for powertrain control to improve fuel economy?
LEVELS OF CONNECTIVITY

- **Driver Assistance**
  - Cruise
  - Steering
  - Brakes

- **High/Full automation**

- **Inter-vehicular communication**

- **Connected infrastructure**

- **System integration**

- **V2V**
  - Surrounding vehicles information
  - Real-time traffic condition
  - Lane condition

- **V2I**
  - Signal Phase and Timing
  - Signalization look ahead
  - GPS data

- **V2X**
  - Cloud-based computation
  - Map and traffic ahead data
  - Route prediction

- **L1, L2**
  - Driver suggestions
  - Vehicle

- **L3, L4**
  - Self driving
  - Self Parking

- **Driver input**

- **Connected infrastructure**
  - GPS data
  - Cloud-based computation

- **System integration**
  - Map and traffic ahead data
  - Route prediction
RECENT ADVANCES LEVERAGING CAV TO ENHANCE FUEL ECONOMY

Commerically Available Technology

• Bosch Electronic Horizon: Predicts required drive energy and controls the engine

• Audi Predictive Efficiency Assistant: Look-ahead GPS control of hybrid (energy management)

• AVL Connected Powertrain: Simulation tools for OEM implementation
RECENT ADVANCES LEVERAGING CAV TO ENHANCE FUEL ECONOMY

- GPS to update and replace road information, adjusting engine control parameters
  - Neuro-Fuzzy derived relief map of test route [6]
- Vehicle position estimation
  - Road slope aid through sensor fusion of GPS and onboard sensors [7]
- Energy management strategy through slope preview
  - Model predictive control with numerical computation for high efficiency operation [8]

8. Yu et al, Model predictive control of a power-split hybrid electric vehicle system with slope preview, Artificial Life and Robotics (2015)
RECENT ADVANCES LEVERAGING CAV TO ENHANCE FUEL ECONOMY

• Trip based power demand distribution in hybrids
  • Driving pattern-based dynamic programming with feedback control for application [9]
  • Deterministic dynamic programming with penalties for fuel consumption [10]

• Traffic data to improve hybrid energy management
  • Neural network model and adaptive equivalent consumption minimization strategy [11]
  • Data-enabled predictive energy management framework [12]

Advances in Literature, cont.

- Adaptive cruise control
  - Nonlinear model predictive control [13]
  - Intelligent: traffic, fuel economy, ride comfort [14]
- Velocity trajectory optimization through look-ahead
  - Satellite navigation, vehicle mass, and road load parameters to estimate and select optimal profile [15]

Further **shape the driving cycle** – end goal of removing the driver from the loop completely

**Trip Data from GPS**

**V2I**
- Current and future terrain
- Real-time and historical traffic information
- Traffic signal phase and timing
- Critical crash scenarios
- Priority assignment for emergency vehicles
- Commercial vehicle enforcement
- Intersection safety

**V2V**
- Position
- Velocity
- Steering-wheel position
- Brake status
- Notice of action
- Right-of-way
Further **shape the driving cycle** – end goal of removing the driver from the loop completely

**Interface Information**
- Right turn into traffic (onto Kinnear Rd.)
- Speed limit 30 MPH
- Traffic signal 555 ft ahead (Kenny Rd.)
- Elevation gain of 14 ft
- Able to turn right at traffic signal (pending traffic)
- Speed limit will be 45 after turn
- Elevation will decrease (<1%) after turn
- Traffic typically moderate on Kinnear Rd. (2 PM on Friday)

**Real-Time Information**
- Traffic currently moderate on Kinnear Rd. (train recently stopped traffic), may be difficult for initial right turn onto Kinnear Rd.
- Traffic signal currently red, will turn green in 7 seconds
- Traffic waiting for light at Kenny (not able to turn right as lead car is continuing on Kinnear)
- Weather: Temp. 77 F, Humidity 57%, Skies Cloudy, Wind 15-20 MPH SSW, Road Status - dry
- Emergency vehicle 2.3 mi SE on Olentangy River Rd. – will need Kinnear Rd. open (87% chance traffic signal and traffic will allow your clearance)
- Train 15 mi S, heading N, will cause delays on Kinnear in ~4 min 25 sec
- Gap of 50 ft between 2nd and 3rd vehicle traveling W on Kinnear – 3rd vehicle slowing down and enabling your entrance onto road
POTENTIAL APPLICATIONS FOR POWERTRAIN CONTROL

From V2V and V2I information, both real time and historical, how should the powertrain be controlled for optimal fuel economy?

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- Gap of 50 ft between 2nd and 3rd vehicle traveling W on Kinnear – 3rd vehicle slowing down and enabling your entrance onto road

- Engine off until gap between 2nd and 3rd vehicle
- Use battery to smooth acceleration torque request on start (battery at full capacity)
- Minimal regenerative braking possible with traffic signal distance, traffic, speed
- Cylinder deactivation enabled due to small duration with expected wait for signal
- Transmission remain in low gear due to traffic, only 555 ft until signal, elevation
- If gap closes or delayed entrance onto Kinnear Rd., remain stationary for emergency vehicle to pass
- With dry roads, moderate weather, and new tires traction should be sufficient for first gear and maximum of 88% torque request (vehicle in front, however, has a flat left rear tire – may cause slow acceleration)
- AC compressor should remain off, if possible, until after speed achieved on Kenny Rd. (elevation decrease), regenerative braking leading to signal at Woody Hayes Dr.
POTENTIAL APPLICATIONS FOR POWERTRAIN CONTROL

• Optimal transmission operation
  • Look-ahead to plan optimal gear selection depending on type of road, road gradient, speed limit,…
• Smart control of auxiliary loads
  • Reduce accessory load in moments of heavy road loads (e.g. steep road)
• Cloud-based computation capabilities
  • Cellular capabilities connect vehicle to cloud-based servers that can perform more advanced calculations
  • Limits the need for on-board computers and allows for virtually unlimited computation
WHAT IS THE SMART CITIES CHALLENGE?

• The U.S. Department of Transportation (USDOT) will make an award of $40 Million to one mid-sized city (between 200,000 and 850,000) that can demonstrate the best vision for how advanced data, applications, and intelligent transportation systems (ITS) technologies can be used.

• Vulcan Inc. will contribute an additional $10 million to incorporate electric vehicle infrastructure.

• Mobileye will install driver assistance safety technology on every bus in the winning city.
Develop smart corridors to demonstrate the capability of intelligent infrastructure to improve transit service and efficiently

Enhance the timeliness and quality of the traffic condition data, complemented by a routing app for trucks to improve the reliability of our highway system for the movement and delivery of freight

Push real time information to users on traffic and parking conditions and transit options to minimize the impacts of concentrated travel demands associated with major events or incidents

Develop and deploy communication technology solutions to address the obstacles that low-income “unbanked” / cash-economy based residents and those who lack smartphone data services face in accessing and using shared and real-time transportation options and app-based services

Expand the usage of electric and smart vehicles through changes to policy and practice and the expansion of our Smart Grid in order to serve our energy and climate change objectives
THE PROCESS
THE MISSION: REINVENTING THE AUTOMOBILE

Improved efficiency, electrification

Reduction in vehicle miles traveled, through intelligence and connectivity

Net carbon free fuels

Increased vehicle intelligence and autonomy

Improved efficiency, electrification

Weight reduction

credit: www.siemens.com/press
AND IF WE FAIL, BACK TO HORSE AND CARRIAGE?
Thank you for your kind attention!

Vielen Dank für Ihre Aufmerksamkeit!

Grazie della cortese attenzione!