NEXTCAR – Next Generation Energy Technologies for Connected and Automated On-Road Vehicles

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Advanced Research Projects Agency – Energy

ARPA-E NEXTCAR Team

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ARPA-E’s Mission

Mission: To overcome long-term and high-risk technological barriers in the development of energy technologies

Ensure U.S. Technological Lead & U.S. Economic and Energy Security

Why is NEXTCAR important to ARPA-E?

21% net efficiency

Estimated U.S. Energy Consumption in 2019: 100.2 Quads

[Diagram showing energy consumption across different sectors]
Transportation Energy Usage

Share of total U.S. energy used for transportation, 2018

U.S. transportation energy sources/fuels, 2018¹

3.2 T miles VMT – 2.85T LD, 0.3T HD
Making future vehicles more energy efficient

This we know how to do:

- Downsize
  - Downweight
    - Improve the efficiency of IC engines
      - Increase hybridization
        - Increase electrification
      - Ultimately full electrification

- What about the effects of vehicle connectivity and automation on future vehicle energy efficiency?

(considering only vehicle-related technologies, and not infrastructure, regulation, policy etc.)

Vehicle Connectivity, Sensing and Automation

- Dedicated short range communication (DSRC) and V2V
  - Provides immediate vehicle ahead information
  - After 2016 US DOT ANPRM, deployment remains uncertain

- V2I, V2X, Cellular (5G), WiFi, Satellite
  - Provides real-time and mid-to-long range routing, weather and traffic data

- Cameras, Radar, LIDAR
  - Provides short range machine vision

- L1-L3 Automation – Throttle, Brake, Steering
Levels of Vehicle Automation

**L0**
- No Automation
  - Zero automation; the driver performs all driving tasks.

**L1**
- Driver Assistance
  - Steerable is controlled by the driver, but certain driving assist features may be included in the vehicle design.

**L2**
- Partial Automation
  - Vehicle has combined automated functions like acceleration and steering, but the driver must remain engaged with the driving task and monitor the environment at all times.

**L3**
- Conditional Automation
  - Driver is a necessity, but is not required to monitor the environment. The driver must be ready to take control of the vehicle at all times with notice.

**L4**
- High Automation
  - The vehicle is capable of performing all driving functions under certain conditions. The driver may have the option to control the vehicle.

**L5**
- Full Automation
  - The vehicle is capable of performing all driving functions under all conditions. The driver may have the option to control the vehicle.

Advanced Driver Assistance Systems (ADAS) are common on new vehicles:
Automated Driving Tasks – L1-L3

‣ **Adaptive Cruise Control**
  - Controls acceleration and/or braking to maintain a prescribed distance between it and a vehicle in front. May be able to come to a stop and continue.

‣ **Lane Keeping Assistance**
  - Controls steering to maintain vehicle within driving lane. May prevent vehicle from departing lane or continually center vehicle.

‣ **Dynamic Driving Assistance**
  - Controls vehicle acceleration, braking, and steering.

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ARPA-E NEXTCAR Program Motivation

Facilitating energy-efficient L1-L3 CAV operation through connectivity and automation to improve vehicle energy efficiency by 20%.
Future Powertrain and Vehicle Dynamic Control with NEXTCAR

Mission
The ARPA-E NEXTCAR Program will fund the development of new and emerging vehicle dynamic and powertrain control technologies (VD&PT) that reduce the energy consumption of future Light-Duty (LD), Medium-Duty (MD) and Heavy-Duty (HD) on-road vehicles through the use of connectivity and vehicle automation.

Goals
• Energy Consumption: 20% reduction over a 2016 or 2017 baseline vehicle.
• Emissions: No degradation relative to baseline vehicle.
• Utility: Must meet current Federal vehicle safety, regulatory and customer performance requirements.
• Customer Acceptability: Technology should be transparent to the driver.
• Incremental System Cost: $1,000 for LD vehicle, $2,000 for MD vehicle and $3,000 for HD vehicle.

Potential Impact
• Energy Consumption Reduction: 4.4 quads/year
• CO₂ Emissions: 0.3 GT/year

Program Director
Dr. Chris Atkinson

Total Investment
$35 Million (2017-2020)
NEXTCAR Portfolio

Light Duty Vehicles

- Gasoline
  - Michigan Tech
    - Connected and Automated Control for Vehicle Dynamics and Powertrain Operation on a Light-Duty Multi-Mode Hybrid Electric Vehicle
  - SwRI
    - Model Predictive Control for Energy-Efficient Maneuvering of Connected Autonomous Vehicles
  - University of Delaware
    - Simultaneous Optimization of Vehicle and Powertrain Operation Using Connectivity and Automation

- Gasoline
  - The Ohio State University
    - Fuel Economy Optimization with Dynamic Skip Fire in a Connected and Automated Vehicle
  - Berkeley
    - Predictive Data-Driven Vehicle Dynamics and Powertrain Control – From ECU to the Cloud

Medium Duty Vehicles

- Gasoline
  - Connected Eco-Box: An Innovative Vehicle-Powertrain ECO Operation System for Efficient Plug-in Hybrid Electric Bus
  - Purdue University
    - Integrated Power and Thermal Management for Connected and Automated Vehicles (iPTM-CAV) Through Real-Time Adaptation and Optimization

- Natural Gas
  - UC Riverside
    - Cloud Connected Delivery Vehicle
  - Penn State
    - Maximizing Vehicle Fuel Economy Through the Real-Time, Collaborative, and Predictive Co-Optimization of Routing, Speed, and Powertrain Control

Heavy Duty Vehicles

- Diesel
  - Purdue University
    - Enabling high-efficiency operation through next-generation controls, systems development for connected and automated class 8 trucks

- Gasoline
  - Connected Eco-Bus: An Innovative Vehicle-Powertrain ECO Operation System for Efficient Plug-in Hybrid Electric Bus
  - Penn State
    - Maximizing Vehicle Fuel Economy Through the Real-Time, Collaborative, and Predictive Co-Optimization of Routing, Speed, and Powertrain Control

Required Capabilities to Replace an Incumbent Vehicle Technology

Any new technology must be comparable to or better than the incumbent in:

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>Power density (or energy density including the fuel/energy storage capacity) ⇒ Customer Acceptance</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Fuel economy or energy efficiency (over real-world dynamic driving) ⇒ Regulation</td>
</tr>
<tr>
<td>Emissions</td>
<td>Regulated criteria pollutants (and CO₂) ⇒ Regulation</td>
</tr>
<tr>
<td>Cost</td>
<td>Total cost of ownership (including capex and energy cost) ⇒ Customer Acceptance</td>
</tr>
<tr>
<td>Reliability</td>
<td>Mean time between failures, maintainability ⇒ Customer Acceptance</td>
</tr>
<tr>
<td>Utility</td>
<td>Acceleration, driveability, NVH, cold or off-cycle operation, ease of use, transparency to the user ⇒ Customer Acceptance</td>
</tr>
<tr>
<td>Fuel Acceptability</td>
<td>Use a readily available fuel or energy source with acceptable range and ease of refueling ⇒ Customer Acceptance</td>
</tr>
<tr>
<td>Safety</td>
<td>Non-negotiable ⇒ Regulation (and Customer Acceptance)</td>
</tr>
</tbody>
</table>
NEXTCAR Industry Ecosystem

- OEMs: TOYOTA, GM, Cummins, HYUNDAI, VOLVO, TRUCKS USA
- Tier-1 Suppliers: BOSCH, Delphi Technologies, APTIV
- System integrators, CAV service providers and others: TULA, SENSYS Networks, Peloton, US Hybrid, WORKHORSE

External Stakeholders at 2019 Annual Review

- Government: Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
- OEMs: FCA, Ford, TOYOTA, DAIMLER
- Tier-1 Suppliers and Equipment Manufacturers: DENSO, Velodyne LiDAR, Infineon, Intel, Valeo
- Testing Services: American Center for Mobility
- Mobility Services: Lyft
- Energy Providers: aramco
- NGO/Consultancy: icct
NEXTCAR Technologies

The NEXTCAR teams have developed the following technologies to achieve an overall 20% energy efficiency improvement:

- **Eco-Routing**
  - Uses GPS, mapping, traffic and weather data to identify the most energy-efficient route for a vehicle to travel between an origin and destination.

- **Eco-Approach and Departure (Eco-AND)**
  - Uses broadcast signal phase and timing (SPaT) data to determine speed optimization between a series of traffic signals.

- **Eco-DRIVE and Eco-ACC**
  - Uses sensing, V2V and/or DSRC to determine the velocity of preceding vehicle(s) thereby avoiding unnecessary braking and other energy consuming maneuvers.

- **Energy Optimization**
  - ICVs and HEVs – Improvements to vehicle efficiency derived through powertrain control optimization (including efficient modal selection).
  - HEVs and BEVs – Improvements to vehicle efficiency and drive range through battery SOC optimization over a full trip.

- **Platooning (for LD and HD)**
  - Uses sensing, V2V and/or DSRC to allow vehicles (≥2) to follow closely together, thus reducing drag and lowering energy consumption of that vehicle group.

In the development process, most teams using:

- Simulation
- Modeling
- SIL
- MIL
- HIL
- Dynamometer in the loop
- On road testing

Including exogenous information & traffic modeling, grade, SPaT etc.
**NEXTCAR Timeline and Critical Milestones**

*Approximate Program Timeline*

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestones</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>Program Development</td>
</tr>
<tr>
<td>2017</td>
<td>Program Kickoff</td>
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<tr>
<td>2018</td>
<td>Vehicles acquired and connectivity features implemented</td>
</tr>
<tr>
<td>2019</td>
<td>Intermediate energy consumption demonstrations</td>
</tr>
<tr>
<td>2020</td>
<td>Final demonstrations to meet program goals (~20% energy consumption improvement)</td>
</tr>
</tbody>
</table>

**NEXTCAR Program Level Results (to date)**

- **Point 1** – bear in mind that all NEXTCAR results are vehicle-specific, vehicle duty cycle, traffic density, technology, penetration rate, weather specific.
  - Not all efficiencies are additive, but some are.
  - These results are presented without context.
    - Results between teams and technologies are not directly comparable (see **Point 1** above).
    - Some results are simulated, some experimental (including HIL, DIL, on-road), some real-world…
- An important consideration: How to gain credit for these EE improvements, if there is no longer a test cycle, per se. Off-cycle credits are one possibility.
### Potential Efficiency Improvements (%)

<table>
<thead>
<tr>
<th>NEXTCAR Technology</th>
<th>MTU</th>
<th>GM</th>
<th>OSU</th>
<th>SwRI</th>
<th>UD</th>
<th>UM</th>
<th>UCB</th>
<th>UMN</th>
<th>UCR</th>
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</thead>
<tbody>
<tr>
<td>Eco-Routing</td>
<td>2-21</td>
<td>7</td>
<td></td>
<td>0-35***</td>
<td>7.7-13.8</td>
<td>12.6-14</td>
<td>12.1</td>
<td></td>
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<tr>
<td>Eco-AND</td>
<td>2-10</td>
<td>8</td>
<td></td>
<td>0-9.8</td>
<td>17.8</td>
<td></td>
<td>31†</td>
<td></td>
<td>9.6-22.9</td>
</tr>
<tr>
<td>Eco-Driving/Cruise</td>
<td>1-7</td>
<td>10-14</td>
<td>13-16*</td>
<td>10-13*</td>
<td>20</td>
<td>12-14</td>
<td>6.8-15.8</td>
<td>0-12.8</td>
<td></td>
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<tr>
<td>Powertrain Optimization</td>
<td>5-12†</td>
<td>2-4**</td>
<td>4.9</td>
<td>12</td>
<td>2-7</td>
<td>9</td>
<td>20.1-21.8</td>
<td>8.5-10.5</td>
<td></td>
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<tr>
<td>Thermal System</td>
<td>4-7</td>
<td></td>
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<td></td>
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<td>2-8</td>
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<tr>
<td>Compact Platooning</td>
<td>1-7</td>
<td></td>
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<td></td>
<td>0-15</td>
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<tr>
<td>Intelligent HVAC</td>
<td>1-28</td>
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<tr>
<td>CACC</td>
<td>1-6</td>
<td></td>
<td>2.6-13</td>
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<tr>
<td>Eco-Stop and Launch (bus application)</td>
<td>10.8-22.9</td>
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*Eco-driving does include power-split.** Indicates improvement only by leveraging dynamic skip firing (DSF). Eco-routing includes power-split optimization over the long horizon.

†MTU powertrain optimization includes optimization of drive unit as well as PHEV blending.

²Charge depleting mode, with an 8.5% increase in travel time on 2.5km arterial.

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**Bear in mind Point 1!**

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**Commercialization Potential**

- ++
- +
- +++
- ++
- ++
- +++
- +
- ++
NEXTCAR Technologies for L1-L3 CAVs

- Predictive Cruise Control
- Power-split optimization
- ECO-Routing
- ECO-Driving
- ECO-AND
- Thermal management optimization
- Platooning

Real World Energy Savings Potential

High
Low

Commercial Potential

Thermal System
Compact Platooning
Intelligent HVAC
Eco-Stop and Launch
Predictive Cruise Control
CACC
Eco-AND
Eco-Driving/Cruise
Powertrain Optimization
Eco-Routing

Low
High

Commercialization Potential
Technology Acceleration Model

NEXTCAR Lessons Learned

- ADAS (L1-L3) has the potential for significant energy efficiency improvements, and it can deliver beneficial short- and medium-term energy reductions.
- More significant energy benefits obtained using vehicle dynamic solutions, than powertrain control.
- Platooning for HD may not yield as much energy benefit as previously envisioned.
- CAV sensing system power consumption is a major parasitic load
  - Current power consumption is >> 1 kWe, which needs to be reduced to <500 We.
NEXTCAR Lessons Learned

‣ **Energy consumption vs. trip time tradeoff** – behavioral aspects are not well understood

‣ **Look-ahead data (connectivity)** is extremely valuable for optimizing vehicle longitudinal control, over a range of timescales.
  – The longer the time horizon (up to the full trip length), the better, but even ‘one vehicle ahead’ (50m+) data is useful.
  – Hierarchy of look-ahead information by timescale – radar/camera, V2V (DSRC or 5G), V2I, V2C.

‣ **Efficiency gains** are vehicle duty cycle-specific, traffic-specific, grade-specific, technology penetration-specific, preview length-specific – but 20% is a readily attainable improvement for ICEs, HEVs and PHEVs.
  – PHEV>HEV>ICE>(BEV).

Current State of the AV Industry

• AV industry is highly dynamic and marching forward with L4-L5 automation

• Various technology leaders have participated in NEXTCAR either as project teams or external stakeholders (shown by the blue circles in the image)
Runaway Energy Usage?

When L4-L5 vehicles become widespread, there is a real chance that we’ll see a substantial increase in energy use due to:

- **A reversion to the primacy of the individually-owned, individually-operated personal vehicle**
- **Higher highway speeds**
- **Increased VMT** due to travel by underserved groups, mode shift from transit, new travel occurring due to lower travel costs, etc.
- **Increased vehicle features** to satisfy passengers, including larger, heavier vehicles and increased on-board loads that increase energy/mile
- **Longer potential commutes** made more practical due to automation.
Mackenzie et al., 2019

NEXTCAR Technologies for L4-L5

- Predictive Cruise Control
- Drive Cycle smoothing
- Power-split optimization
- ECO-Droving
- ECO-AND
- Platooning
- Thermal management optimization

Real World Energy Savings Potential

Commercial Potential
How relevant is NEXTCAR today?

INRIX traffic data

Nextcar Summary

- NEXTCAR has achieved significant results across a range of technologies.
- The motivation for NEXTCAR is more relevant than ever right now.
- Commercialization success is the next critical step.

- NEXTCAR Field Demonstration Days?
- Other avenues for dissemination of information – conferences, workshops, papers, demonstrations.

- ARPA-E is always interested in energy efficiency technologies – anticipate OPEN 2021.
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