NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Leveraging Intelligent Vehicle Technologies to Maximize Fuel Economy

SAE Electronic Systems for Vehicle Propulsion (ESVP) Symposium

Presented by:

Jeff Gonder

Center for Transportation Technologies & Systems (CTTS)

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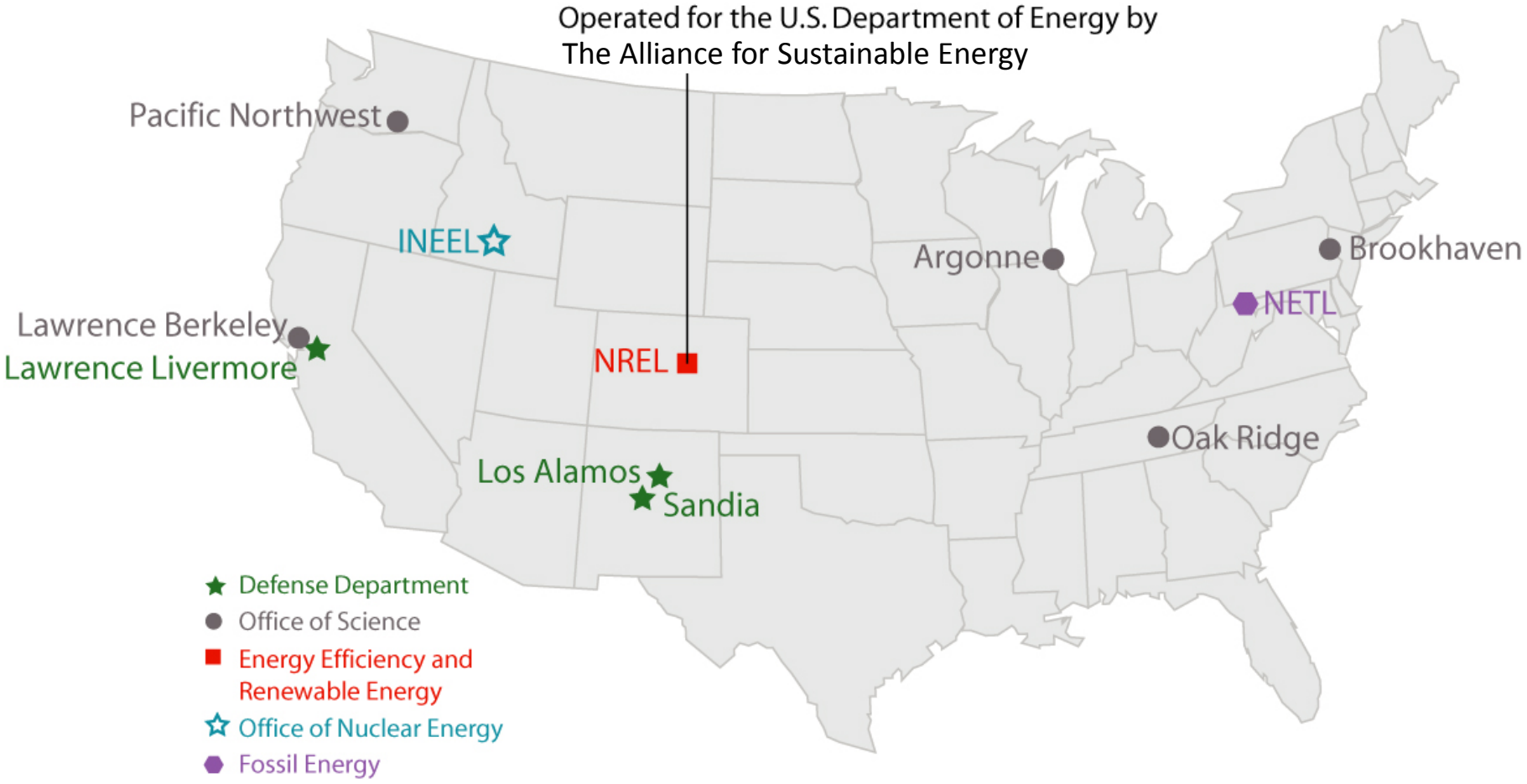
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

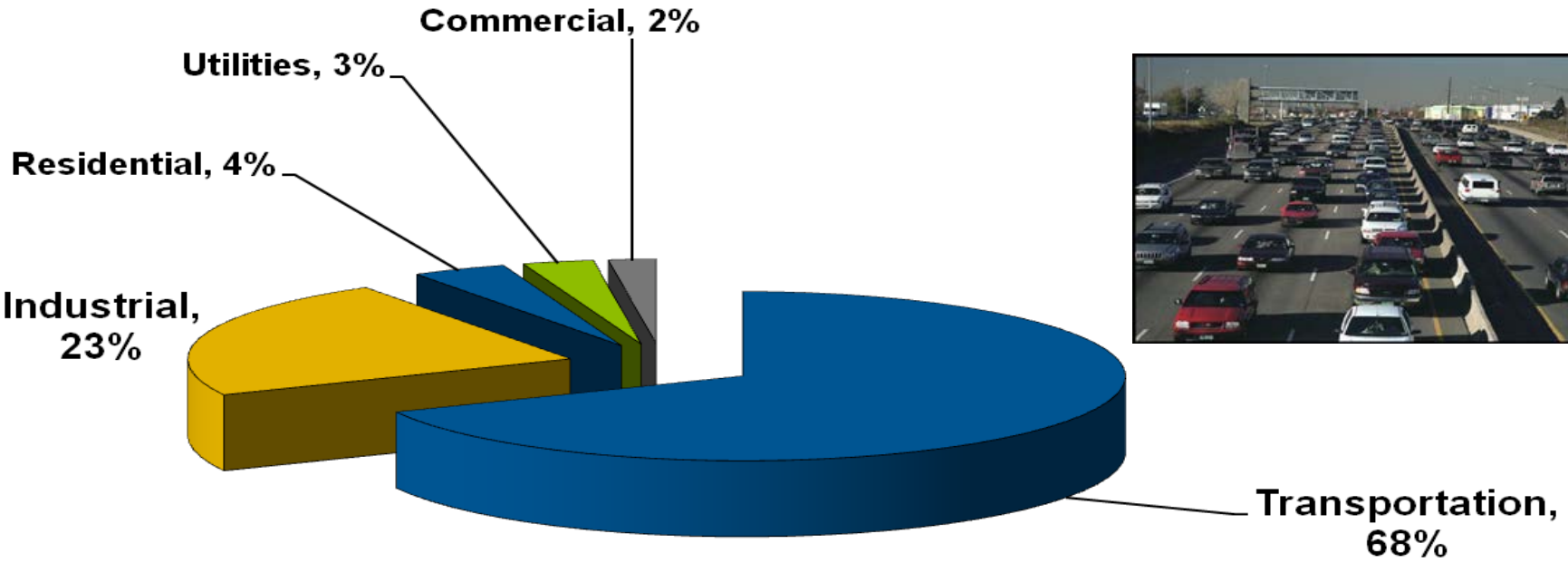
Presentation Outline

- NREL/CTTS mission space
  - Variety of transportation/vehicle efficiency research topics
- Opportunity presented by intelligent vehicle technologies
  - Range of fuel-saving applications
- Deep dive into driver feedback research project
  - Quantifying savings potential
  - Understanding driver receptiveness factors
  - Assessing feedback approaches
  - Recommendations to maximize fuel savings
- Concluding thoughts
  - Potential long-term synergies

NREL is one of the U.S. DOE's national research laboratories



Fuel Efficiency Research Motivation: Daily demand for fuel



Daily Oil Consumption

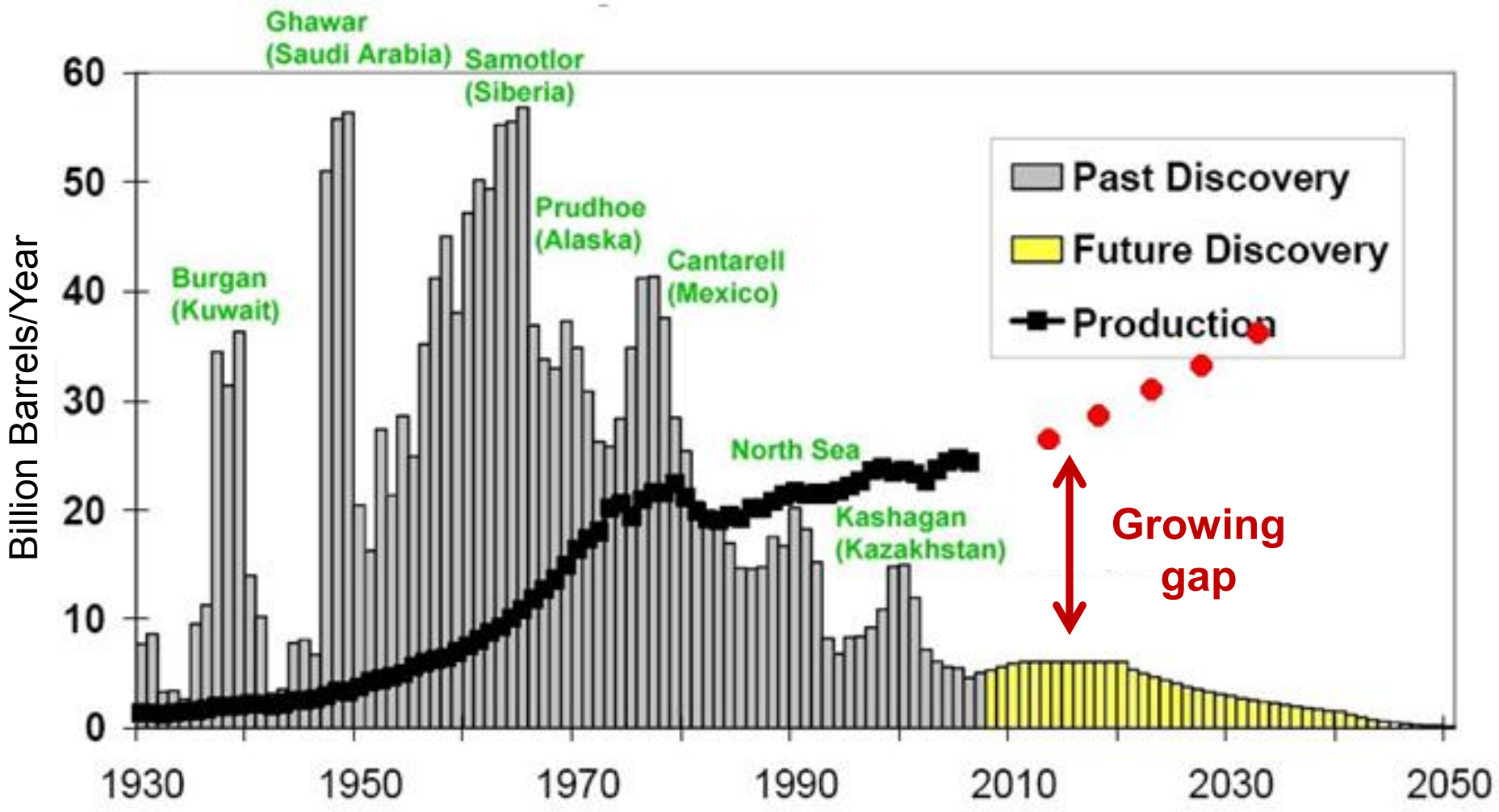
Light-Duty Vehicles
8 M barrels

58% of transportation consumption
42% of all oil use

All Uses
84 M barrels globally
19 M barrels U.S.

Heavy-Duty Vehicles
2.5 M barrels

Fuel Efficiency Research Motivation: Declining resources



The Association for the Study of Peak Oil and Gas, Newsletter No. 97, April 2009
http://aspoireland.org/newsletter/

Transportation research includes fuel source and vehicle efficiency

Advanced biofuels

Gas to liquid

Conventional

Engine fuel effects

System optimization

Accessory loads

Fuels

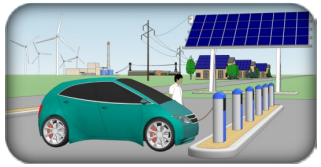
Vehicles

Natural gas

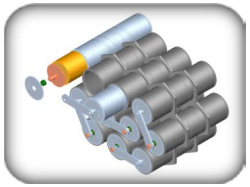
Hydrogen

Electricity

Vehicle-grid integration



Batteries



Electric motors

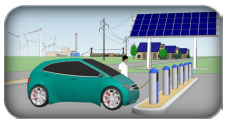
Also consider efficiency-improvement opportunity from affecting operating profiles

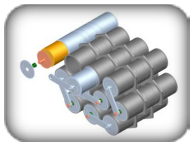
Adaptive intelligent control

Efficient route planning

Vehicles

Driving profiles





Driver feedback

Traffic flow improvements and incident reduction

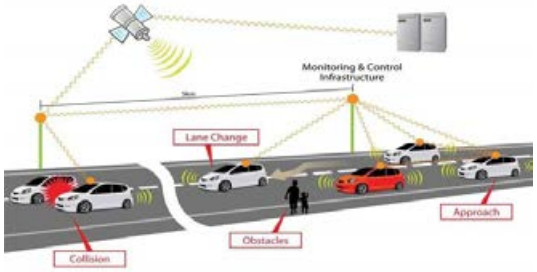
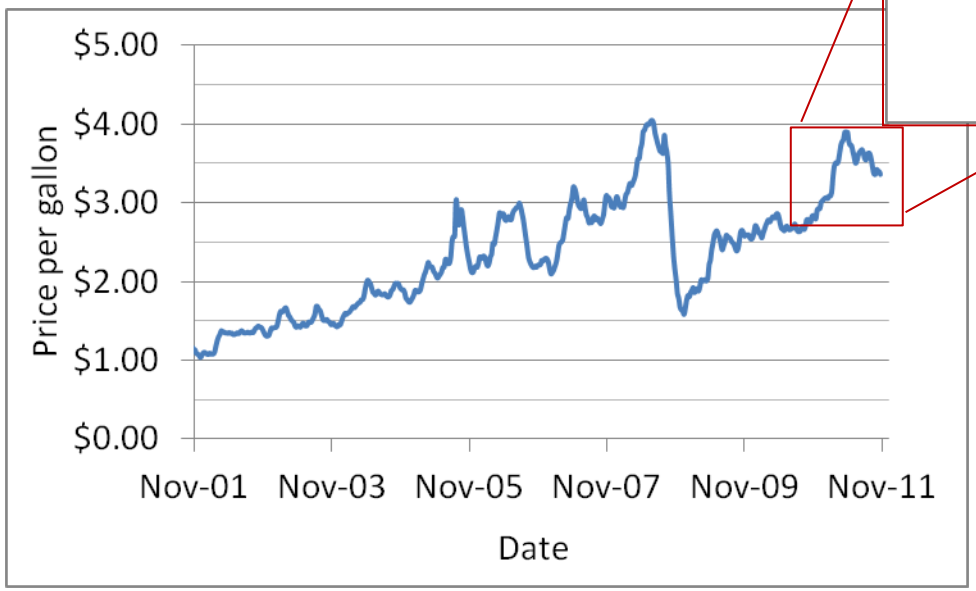
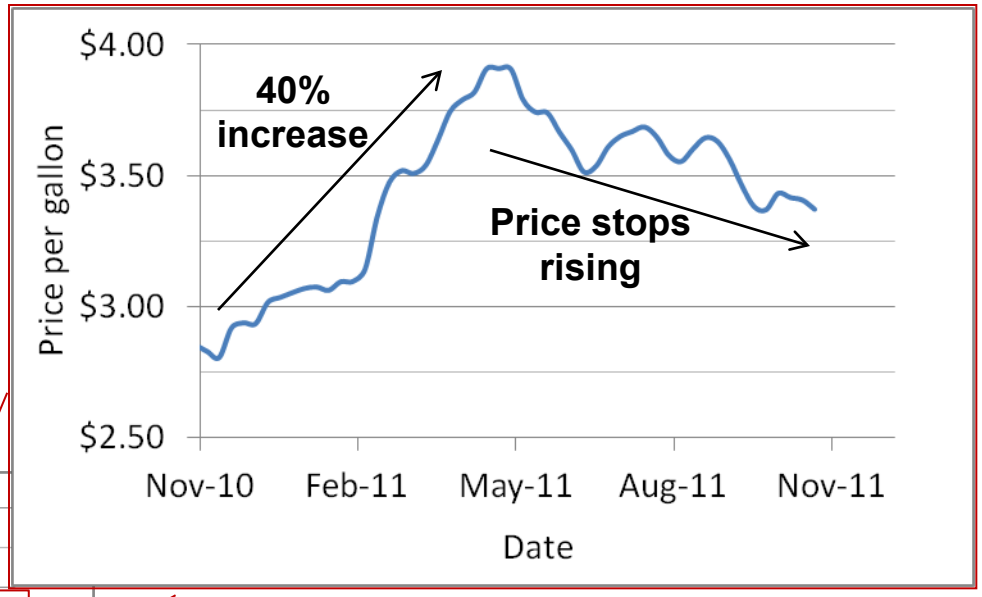


Image sources in notes section

Consider consumer fuel efficiency interest – tied to fuel price … or price changes

"Shock" when price rises





"Trance" when price goes down

Data from www.eia.doe.gov

Photos from iStock/7440389 & 7440392

Intelligent Vehicle Technologies: Potential to get fuel savings without having to "sell" fuel savings

Vehicles

Adaptive intelligent control

Efficient route planning

Driving profiles

Driver feedback

Traffic flow improvements and incident reduction

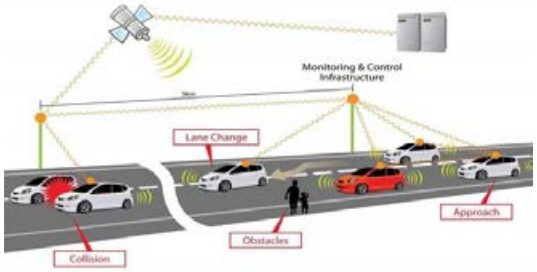


Image sources in notes section

Rationale for Adaptive Intelligent Control

Save fuel

- NREL simulations demonstrated 2%-4% HEV fuel savings
- PHEV savings could be even higher
  - Driving type and distance important
  - FY12 modeling and hardware project

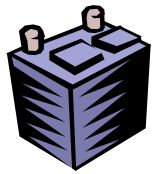
Cost-effective

- Significant recurring costs for alternatives with similar fuel savings
  - Lightweight materials, high-efficiency components, etc.
- Control intelligence requires only software changes
  - Low cost → wide penetration possible

Additional benefits possible

- Emissions reduction from pre-emptive engine start
  - Avoid starting HEV/PHEV engine cold/under significant load

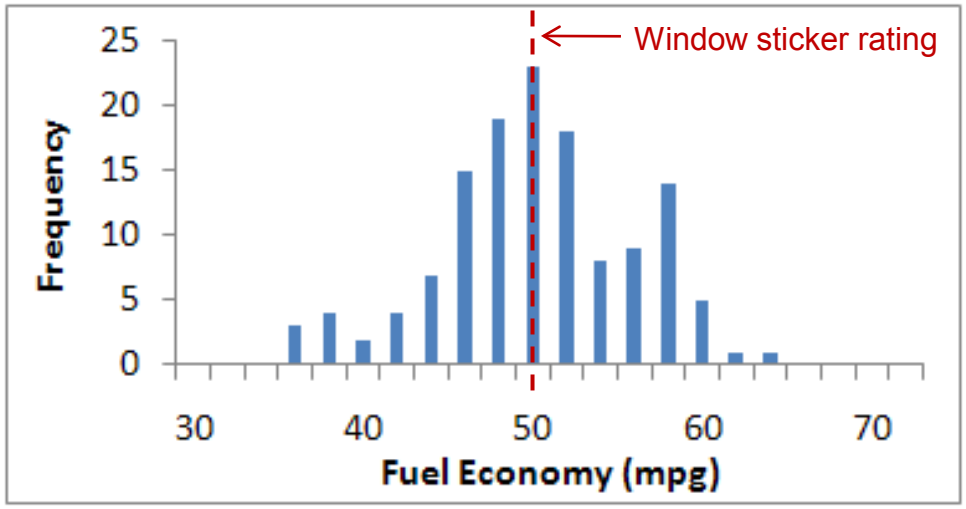
- Improved battery life
  - Advanced cycle knowledge could also help minimize battery wear



Rationale for Driver Feedback

"Your mileage will vary" based on driving style

2010 Prius Fuel Economy Histogram for 133 Drivers*



Stands to reason that broad adoption of efficient habits could have large aggregate fuel savings benefit

- Shift overall MPG distribution higher for all vehicles
  - Some distribution will remain due to factors such as weather, traffic, etc.

* Data accessed from www.fueleconomy.gov on March 9, 2011

National Benefit Comes from High Penetration

>200 million existing vehicles, often in service >15 yrs

- New technologies take a while to penetrate the fleet
- Improving efficiency of current vehicles can have a broad impact
- Fleet mpg will be slow to change without addressing legacy vehicles

Photo from iStock/11994853

Photo from iStock/ 3004844

Large aggregate benefit from 10% better mpg

- 300 million barrels/year petroleum savings
- $30 billion/year (at $100/barrel)

Driver Feedback Project Approach

- Quantify savings from cycle changes
  - Vehicle simulations
  - On-road experiments over repeated routes
  - Consider potential from individual profile improvement and prevalence of sub-optimal driving
- Identify/understand behavior influences
  - Literature review & expert consultation
  - Observe factors impacting on-road decisions
- Assess feedback methods
  - Survey existing examples
  - Evaluate based on project's other findings
- Develop recommendations

Midsize Conventional Vehicle Assumptions
(Used model from a previous study)

Engine = 123 kW	CD = 0.30
Curb mass = 1473 kg	Crr = 0.009
FA = 2.27 m^2	

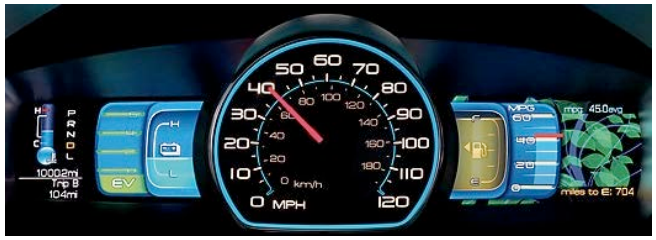
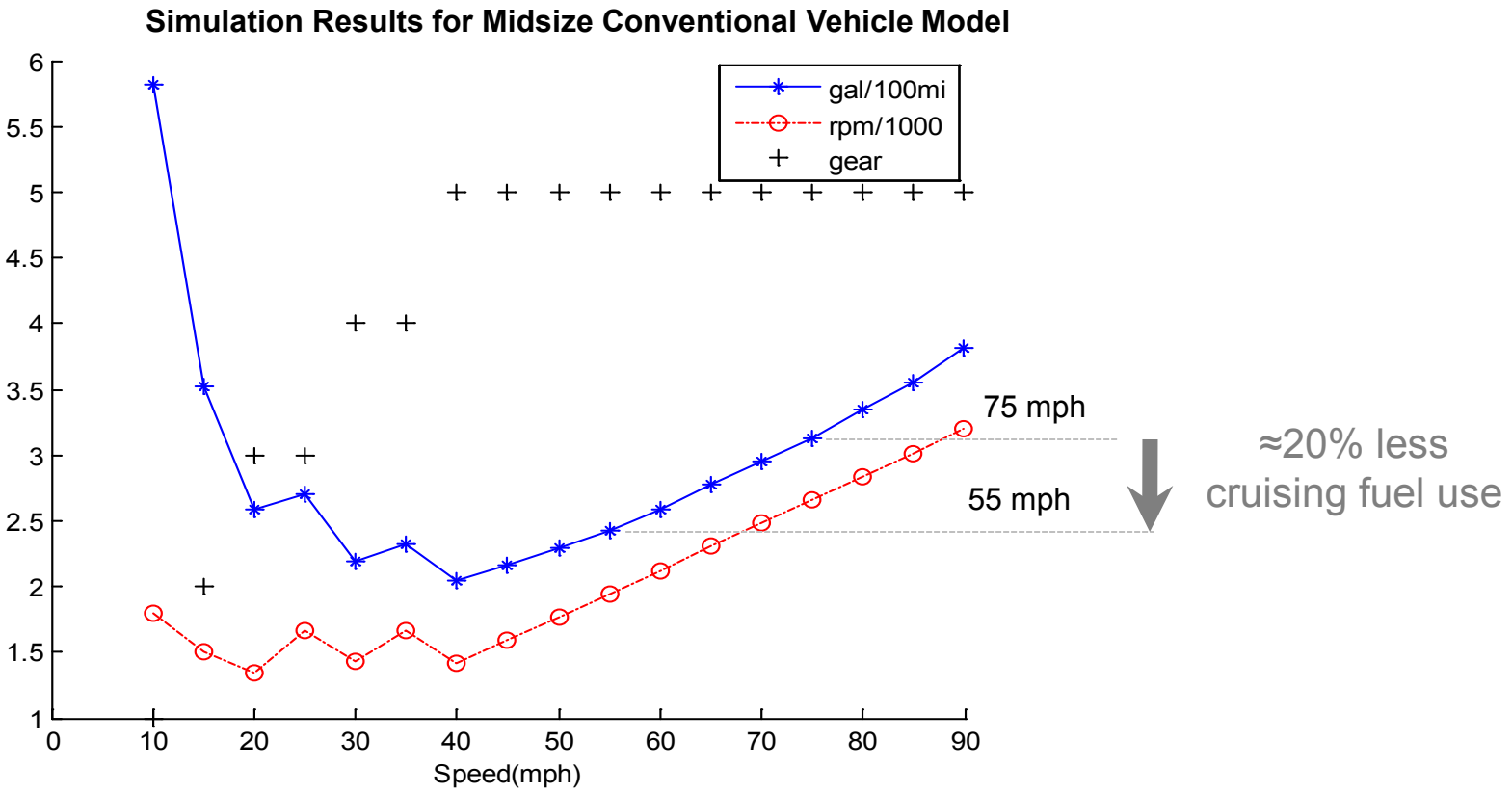


Image sources in notes section

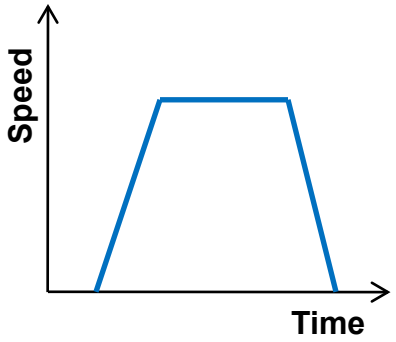
Cruising Speed Evaluation:
Optimal fuel efficiency at mid-range speed

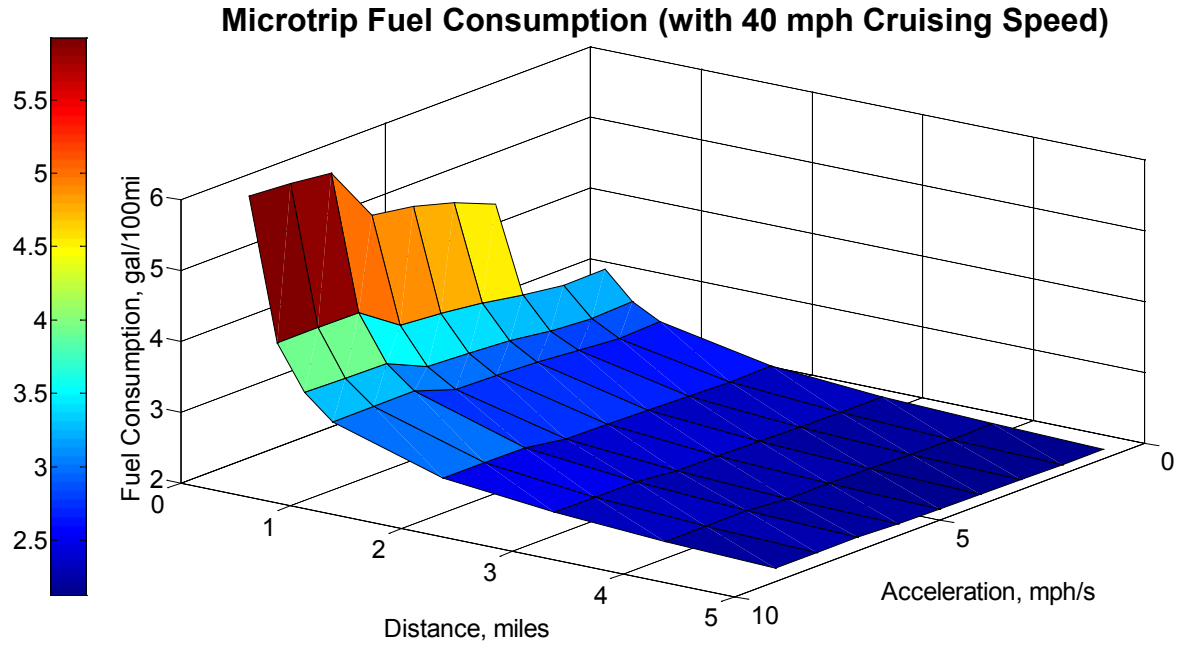
- Consumption lowest between roughly 20-55 mph
  - Optimal ≈40 mph for this vehicle



Acceleration Evaluation: Lower efficiency and higher acceleration sensitivity from "stop-and-go" driving

- Controlled microtrip simulations (accel, cruise, decel back to stop)
  - Sensitivity of microtrip distance and acceleration rate
- Results consistent with qualitative expectations
  - Better fuel efficiency from longer distances (more cruising)
  - Acceleration sensitivity for short distances (stop-and-go)
    - Higher acceleration → worse fuel economy

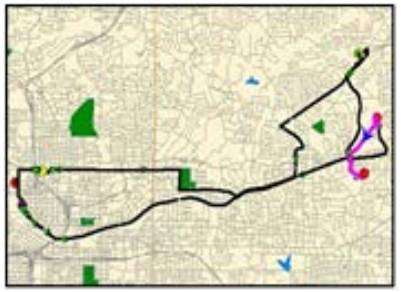




Real-World Cycle Evaluation

GPS travel data from NREL-hosted data center

- E.g., 2006 survey in San Antonio and Austin, TX
- 783 full-day, sec-by-sec drive cycles
- Captures real-world speeds, accels, distances, etc.



Consider a few representative cycles

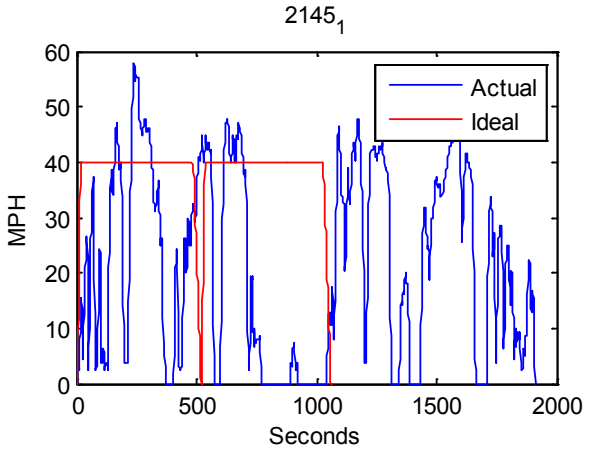
- Across range of kinetic intensity (KI)
  - KI is a useful cycle classification parameter representing the ratio of characteristic acceleration to aerodynamic speed [O'Keefe et al. 2007]

Cycle Characteristics

Cycle Name	KI (1/mi)	Distance (mi)	Aerodynamic Speed (mph)	Characteristic Accel (mph/s)	Stops per Mile	% Idle Time
2012_2	4.55	1.3	19.1	0.46	3.91	35.3%
2145_1	1.03	11.2	37.2	0.40	0.71	11.6%
4234_1	0.87	58.7	43.2	0.45	0.73	14.9%
2032_2	0.24	57.8	59.0	0.23	0.21	6.4%
4171_1	0.16	109.4	65.7	0.20	0.21	7.5%

GPS = global positioning system

Outer Bound Savings from "Ideal" Cycles



- Applied ideal adjustments to real-world cycles
  - Eliminated unnecessary idling and stop-and-go
  - Optimized acceleration rate and cruising speed
- Dramatic 30%-40% fuel savings possible
  - With same vehicle and powertrain
  - Would require vehicle/traffic flow automation to actually achieve

Simulated Conventional Vehicle Fuel Savings for Ideal vs. Real-World Cycles

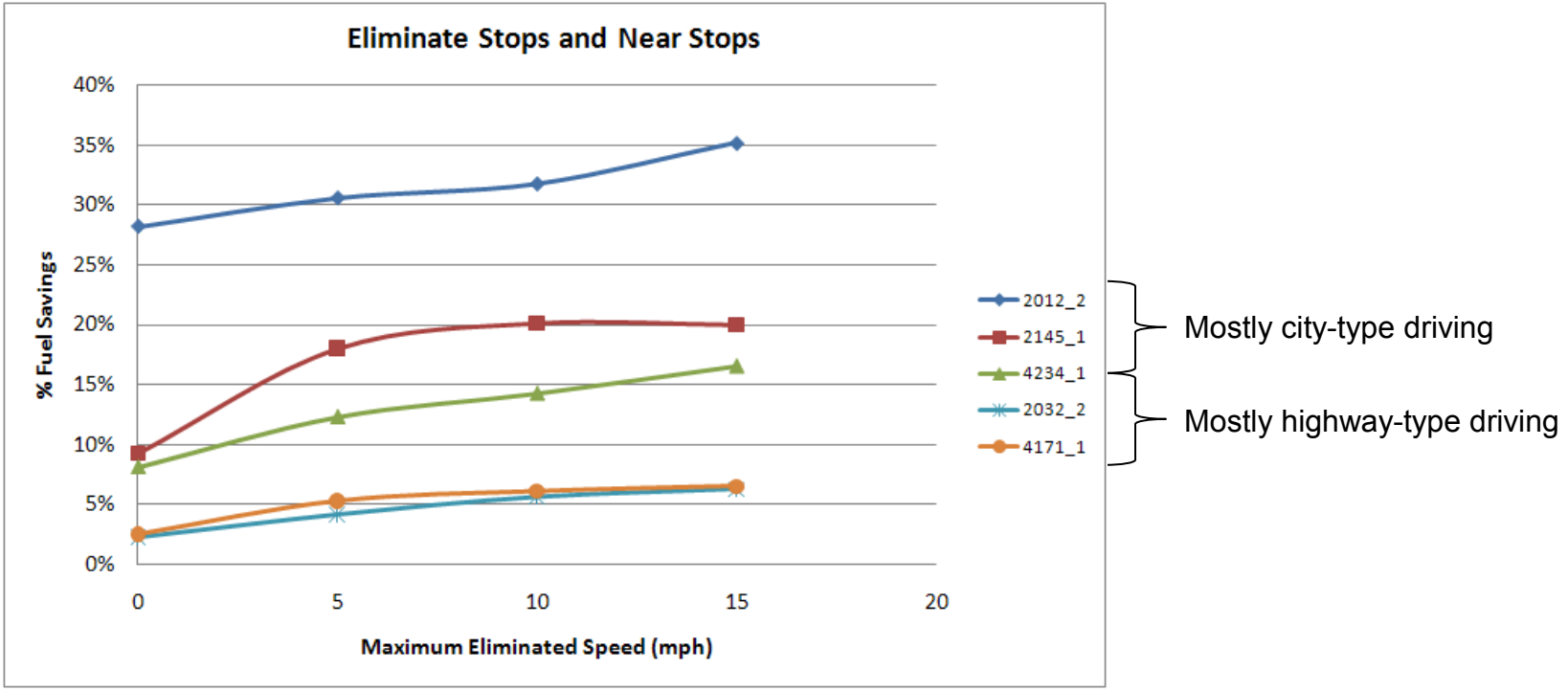
Cycle Name	KI (1/mi)	Distance (mi)	Fuel Economy (mpg)		% Increase	Gallons Used		% Decrease
			Real World	Improved		Real World	Improved	
2012_2	4.55	1.3	17.0	39.5	132%	0.08	0.03	**57%**
2145_1	1.03	11.2	31.0	49.8	61%	0.36	0.22	**38%**
4234_1	0.87	58.7	30.5	52.7	73%	1.92	1.11	**42%**
2032_2	0.24	57.8	35.2	52.7	50%	1.64	1.10	**33%**
4171_1	0.16	109.4	32.7	53.1	62%	3.34	2.06	**38%**

- On today's roads only incremental cycle improvements achievable

Isolating Cycle Improvement Savings:
Contribution from eliminating stop/slow-and-go

Accel/Decel = dominant efficiency factor in urban driving

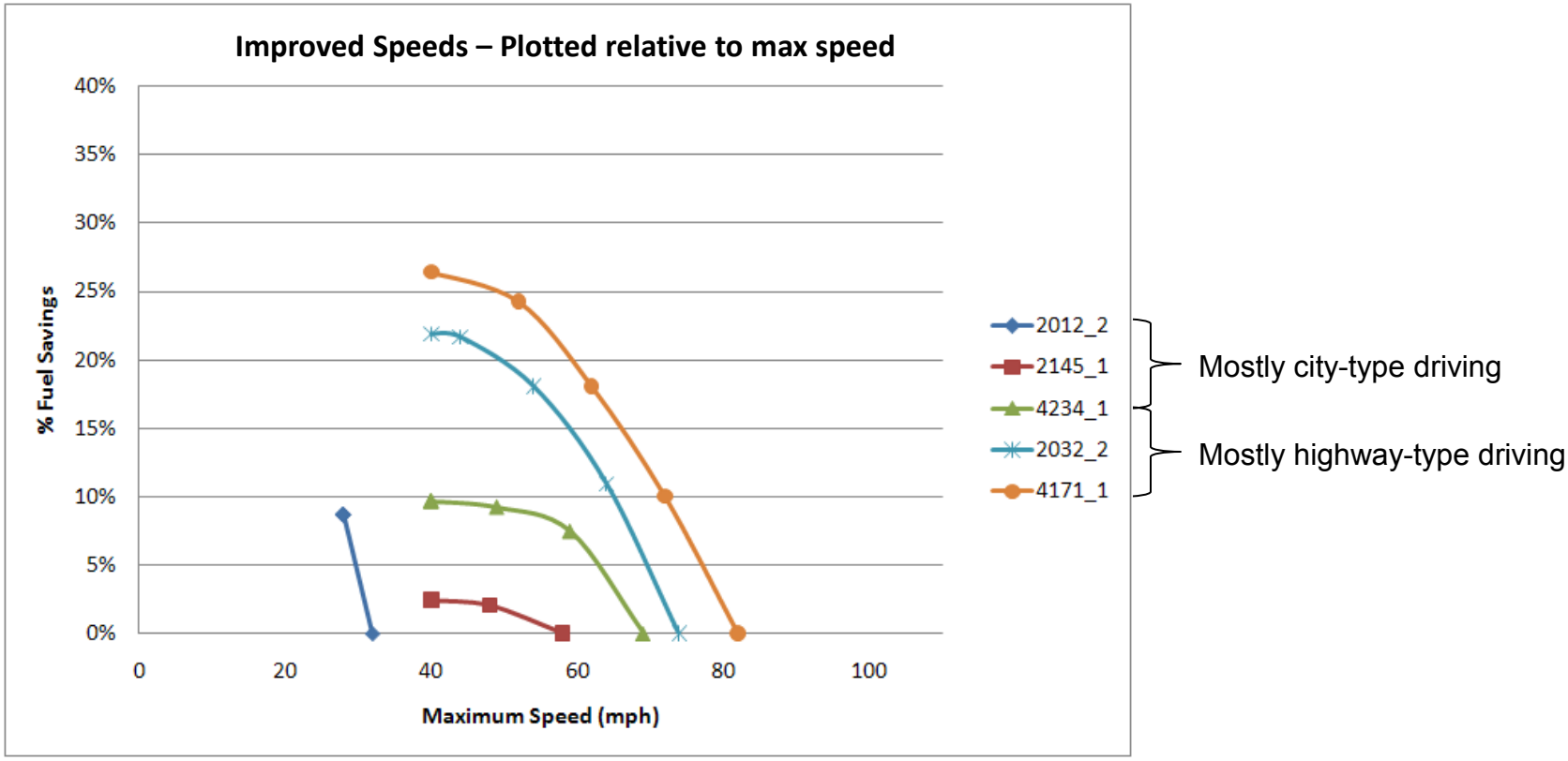
- Reduce frequency of stop/slow-and-go through cycle smoothing
  - Possible by paying attention farther ahead (e.g., slightly slowing early to avoid getting stopped at a red light)
- Reduced accel/decel rate is a secondary effect



Isolating Cycle Improvement Savings:
Contribution from speed optimization

High speeds = important factor in highway driving

- High aero drag at extreme speeds leads to large fuel use
- Savings related to magnitude of original speed relative to optimal speed

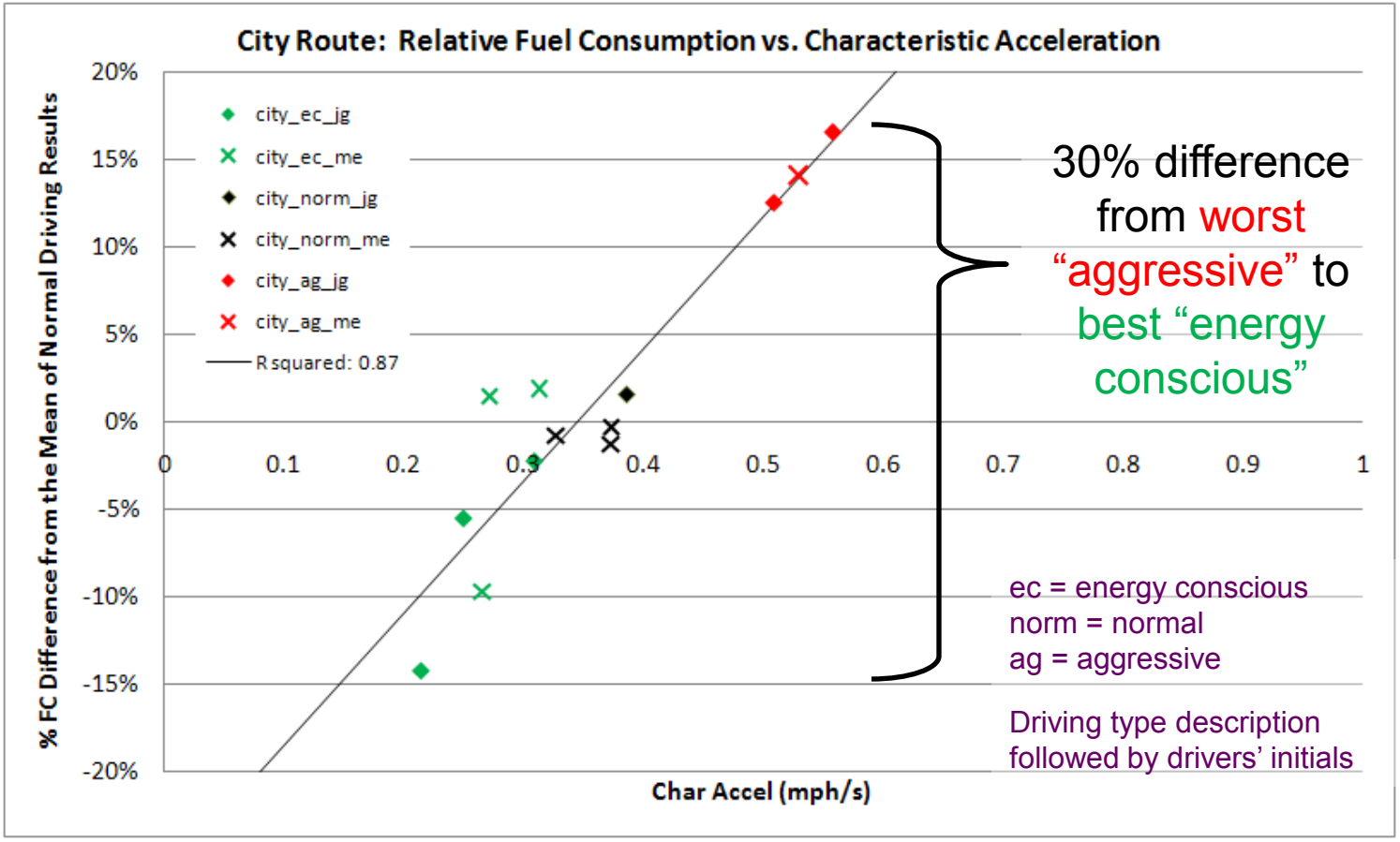


aero drag = aerodynamic drag (proportional to velocity squared)

On-Road Repeated-Route Testing

Confirming savings achievable from different driving styles

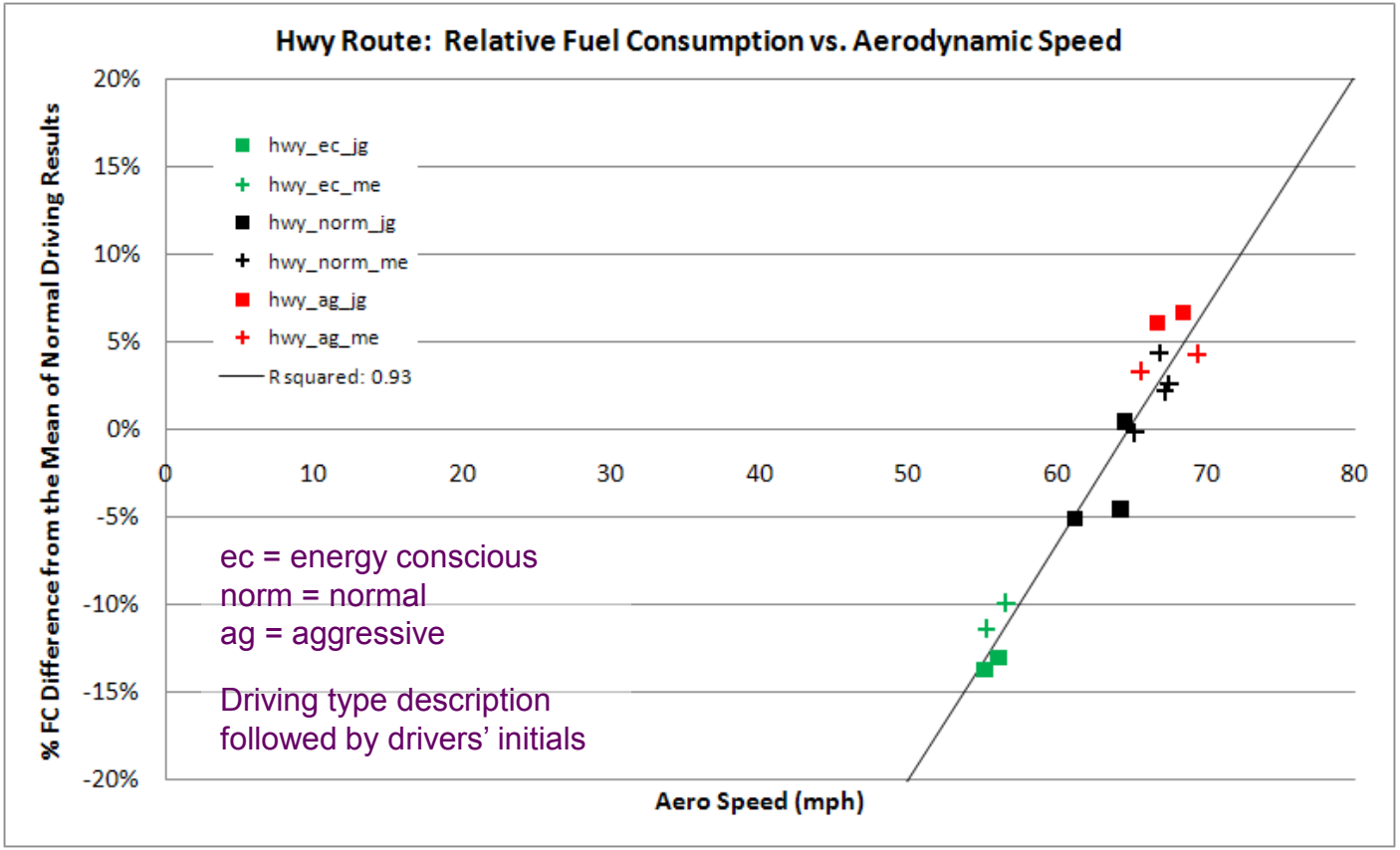
- Clear savings benefit for energy conscious vs. normal vs. aggressive
  - Though considerable spread within each driving type
- Savings correlate with acceleration on city route



On-Road Repeated-Route Testing

Confirming savings achievable from different driving styles

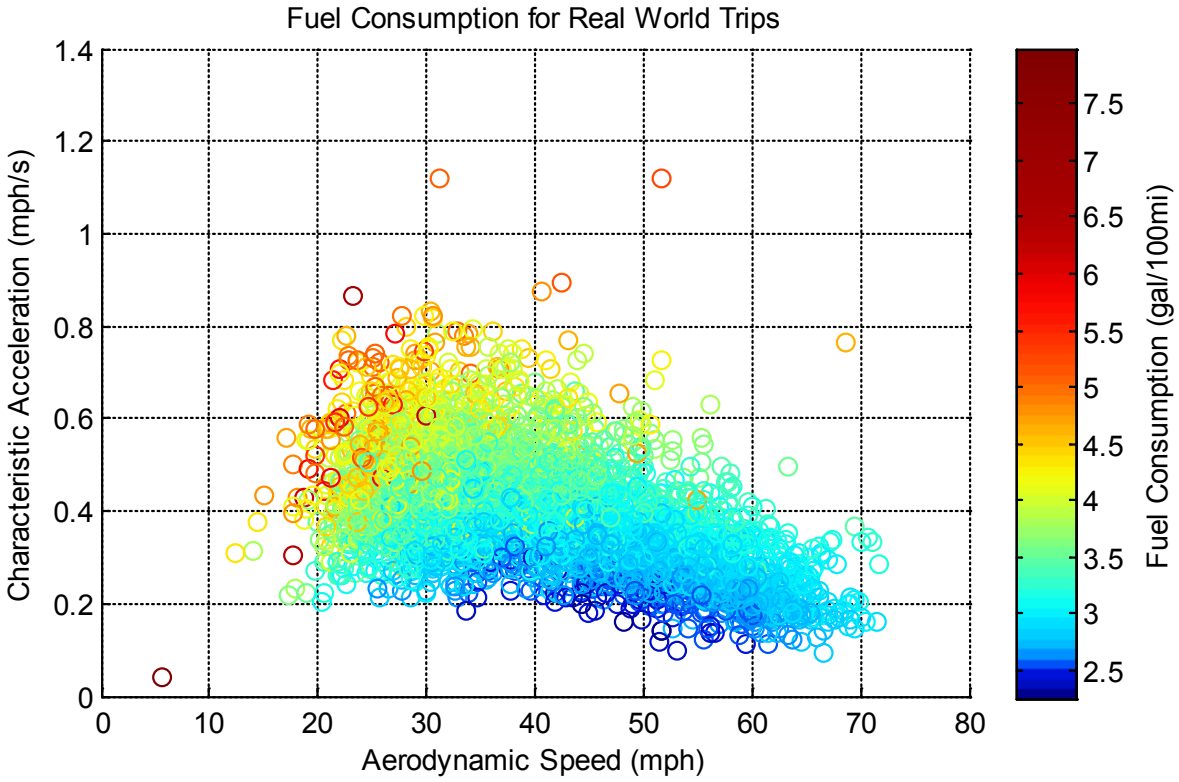
- Similar findings for highway route
  - Less total spread (20%), but top speed in “aggressive” testing much lower than many extreme speeds observed in the real-world sample
- Savings correlate with speed on the highway (hwy) route



Prevalence of Inefficient/Suboptimal Driving

Real-world sample separated into nearly 4,000 trips

- Evaluated prevalence of inefficient behaviors
  - Primarily high accel in urban and high speed in highway driving
  - Low urban speeds and high highway accelerations also play a role



Evaluating Driver Receptiveness to Feedback

Consulted with social science experts for advice

- University of Colorado, Institute of Behavioral Science
  - Lessons learned from analogous studies of building energy efficiency feedback devices

IBS INSTITUTE OF BEHAVIORAL SCIENCE ■ UNIVERSITY OF COLORADO AT BOULDER ■ BOULDER, COLORADO ■

- Gloworm Insights
  - Recommendations for evaluating human factors/ design issues for driver feedback approaches

Gloworm

- Bottom line: Need to understand driver influences
  - Why existing behaviors chosen
  - What may be barriers to change

Literature Review Insights:
Driving behavior influences and issues

- Driving influences on road load and fuel-saving potential
  - Similar findings to NREL analyses
  - Suggest multi-faceted approach needed (driver feedback, policy, incentives, marketing, etc.)
- Effect of social norms
  - Deviation from median increases accident likelihood
  - Positive pressure from peer comparison can help
- Potential adoption and use of feedback systems
  - Interest closely tied to fuel price
  - May need to provide additional incentive
  - Finite time window in which user will pay attention to device
- Potential driver distraction
  - Voice/audible feedback can help minimize
  - Also important to minimize required cognitive load

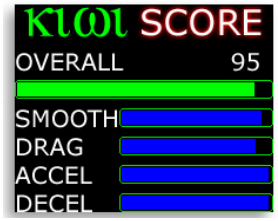
Driving Style Considerations:
Observations from on-road driving experiments

- Mild accelerations and speeds can annoy people
  - Angry honks during two out of eight energy-efficient drives
  - Free-flow traffic generally exceeds the posted speed limit
- Various impacts of even light vs. moderate traffic volume
  - Light traffic makes efficient driving easier for motivated drivers, but harder for unmotivated drivers (other cars zip by rather than tailgate)
  - Heavier traffic can increase stop and go for all vehicles, but may limit excessive fuel use from aggressive drivers
- Other important factors
  - Time urgency – running late leads to more fuel use; efficient driving easier for relaxed tourist/"Sunday drive"
  - "Difficult" to only lightly push into pedal for powerful vehicles
  - Financial hardship may motivate mode change before driving style change

Photo from iStock/793722

Assessed Existing Feedback Approaches

- OBD-connected aftermarket devices
  - PLX Kiwi
  - Eco Way



- Smart phone apps
  - DriveGain
  - GreenMeter
- OEM dashboards
  - Some: MPG only
  - Hybrids: Extensive info.

- GPS navigation devices with integrated feedback
  - Garmin Eco-Route
- Offline analysis/driver training
  - Driving Change by Enviance
- Haptic pedal feedback
  - Ford SAE paper
  - Nissan ECO Pedal

DRIVING CHANGE
Reducing Vehicular CO2 Emissions

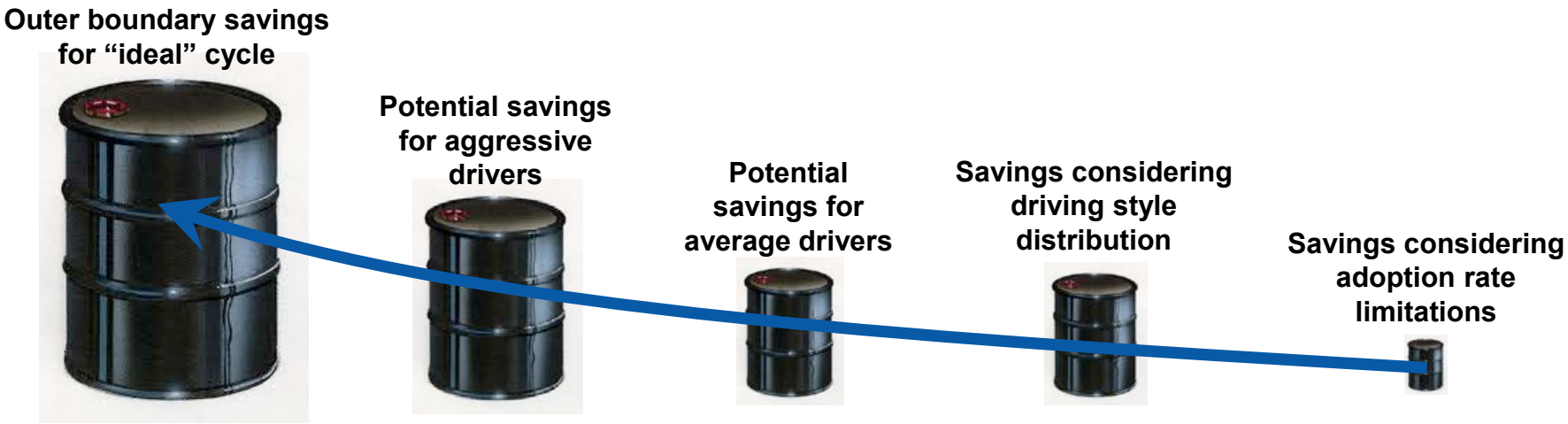
OBD = on-board diagnostic port; OEM = original equipment manufacturer; See notes section for image sources

Evaluation Summary

- Test/review devices in context of project findings
  - Can the approach work?
    - Accurate information and instruction conveyed effectively?
  - Are people likely to use it?
    - Easy to use?
    - Avoids unintended consequences?
    - Helps trump other behavior influences?
- Found penetration rate hurdles even for “best” approaches
  - Dashboard feedback
    - Few vehicles equipped with robust systems
  - Smartphone and OBD
    - Requires purchasing/repurposing and mounting device

Key Study Findings

- Driving changes can save fuel
  - 30%-40% outer bound for “ideal” cycles
  - 20% realistic for aggressive drivers
  - 5%–10% for majority of drivers
- Existing methods may not change many people’s habits
  - Other behavior influences dominate
  - Limited reach potential for evaluated approaches



Developed several recommendations to maximize savings…

Recommendation 1: Leverage applications with enhanced incentives

Commercial vehicle fleets

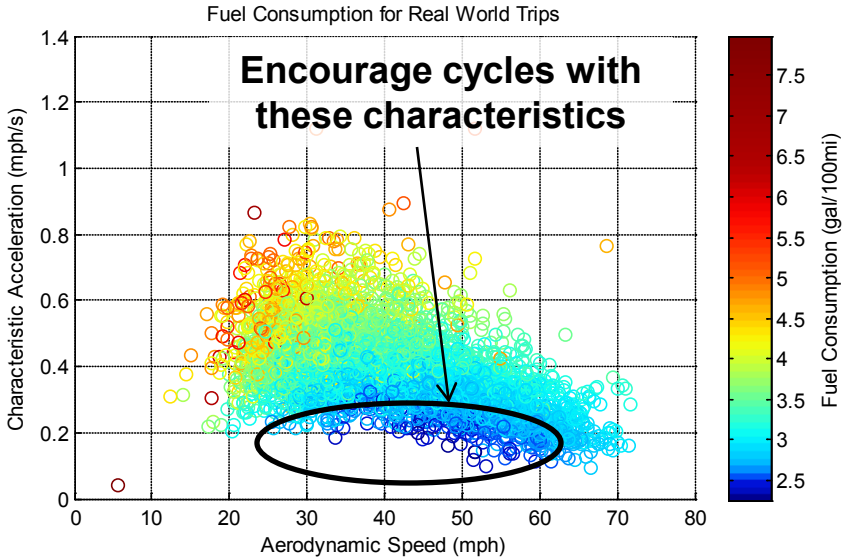
- High fuel-savings motivation
  - Strong connection to bottom line
- Fleet managers can influence driver behavior

Usage-based insurance

- Helps insurers better assess risk
  - Policyholder discounts exchanged for measurements of distance driven, frequency of high speeds and accelerations, etc.
- Potential double benefit for drivers
  - Same factors increase fuel use and insurance risk
  - Behavior change could reduce fuel and auto insurance expenses
- Insurer would make sure feedback does not create driver distraction

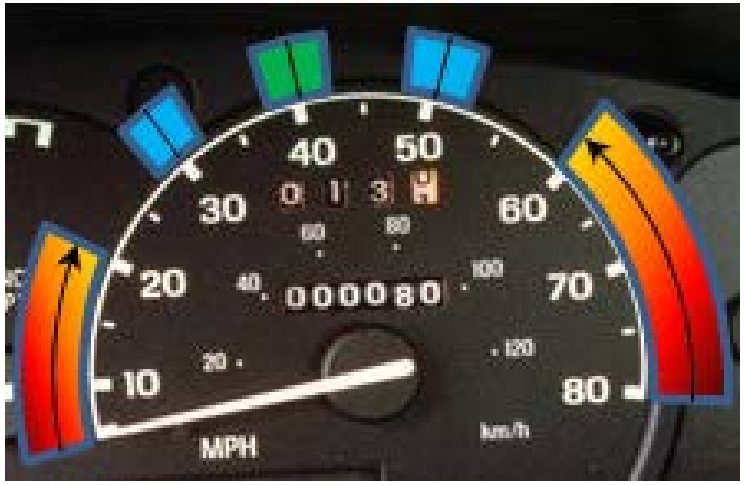
Photos from iStock / 7734733 & www.progressive.com

Recommendation 2:
Prepare a simple and widely deployable approach



- Rising fuel prices could increase receptiveness to efficiency instruction
- Effective approach could combine general advice with reference points added to existing vehicle gauges, e.g.:

1) Watch the road, obey the law, and **drive safely** (contributing to an accident will NOT save fuel).
2) **Avoid speeds below ~20 mph and above ~60 mph** (mpg progressively worsens in these regions).
3) **Hold speed** at a **steady** value in the 25-55 mph range (e.g., keep centered on or between the color bars).
4) **Slow down** by letting off on the gas rather than by using the brake, and do so **early** to minimize time at very low speeds.
5) Above 10 mph, accelerate slowly (so that at least 2–3 sec passes for every 10 mph increase in speed).
6) Turn off engine when parked (do not idle).



Modified from PIX 05472

Recommendation 3:
Make it increasingly automatic

Implement "green driving assist" feature

- Similar to other advancements giving the vehicle more responsibility
  - Lane keep assist
  - Adaptive cruise control
  - Emergency braking for collision avoidance
  - Automated parking
  - Etc.
- Leverage sensors/connected vehicle technology
  - Radar
  - Laser
  - Camera
  - ITS/V2I communication

Mercedes commercial

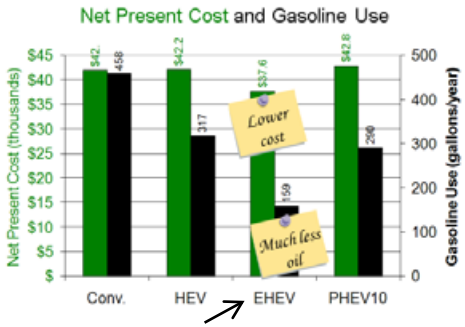
ITS = intelligent transportation system; V2I = vehicle to infrastructure

Food for Thought:
Achieve outer bound savings through further automation

- Dramatic recent advancements (battlefield- and safety-driven)

- Added value would drive <u>demand</u> (independent of fuel price)

- Dramatic and compounding fuel savings
  - Large cycle smoothing benefit (30%–40%)
  - Light-weighting and powertrain downsizing
  - Facilitate roadway electrification and/or car sharing



Electric roadway analysis

See slide notes for source information

Questions?

Special Thanks To:

- Dr. Yury Kalish, David Anderson and Lee Slezak
  DOE Vehicle Technologies Program

NREL Contact:

- Jeff Gonder – jeff.gonder@nrel.gov

Additional Slide

GPS Drive Cycle Data Availability

From the NREL-hosted Transportation Secure Data Center (TSDC)

www.nrel.gov/vehiclesandfuels/secure_transportation_data.html

- Secure archival of and access to detailed transportation data
  - Travel studies increasingly use GPS → valuable data
  - TSDC safeguards anonymity while increasing research returns
- Various TSDC functions
  - Advisory group supports procedure development and oversight
  - Original data securely stored and backed up
  - Processing to assure quality and create downloadable data
  - Cleansed data freely available for download
  - Controlled access to detailed spatial data
    - User application process
    - Software tools available through secure web portal
    - Aggregated results audited before release

NRC report*

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GPS = global positioning system

* See recommendations from this 2007 National Research Council report: books.nap.edu/openbook.php?record_id=11865