Sustainable Transportation Energy Pathways Research

Prof. Joan Ogden (jmogden@ucdavis.edu)

TTP Orientation Seminar

November 21, 2014

$H_2$
Addressing Transportation Energy Challenges

*Climate change, Air quality, Energy security*

### Reduced Vehicle Miles Traveled (VMT)
- Carpooling
- Mass transit
- Urban design
- Intelligent Transportation Systems (ITS)

### Vehicle Technology
- Advanced conventional vehicles (ICE)
- Plug-in hybrid electric
- Battery electric
- Fuel cell electric

### Fuel Alternatives
- Hydrogen
- Biofuels
- Electricity
- Low-carbon liquid fuels (coal / NG with sequestration)

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*A comprehensive energy strategy should have a “portfolio” approach with multiple solutions*
POTENTIAL FOR VEHICLE ENERGY EFFICIENCY (ICEVS 2X +)

FUTURE FUEL/VEHICLE PATHWAYS (ROAD VEH.)

Diagram illustrating the various fuel and energy pathways for future vehicles. The primary sources are Oil, Coal, Natural Gas, Biomass, Solar, Wind, Hydro, Ocean, and Geothermal. The energy carriers include Gasoline, Diesel, Synthetic Liquids, Methanol, CH4, Ethanol, Electricity, and H2. The types of vehicles include ICEV, HEV, Plug-in HEV, Battery EV, and Fuel Cell EV.
Transport Fuels Today (94% petro-based, 2% biofuel)
IEA ETP 2012: THREE ENERGY SCENARIOS
6 DS (Current Policies), 4 DS, 2DS

Figure 1.3
ETP 2012 scenario CO₂ emissions pathways

Key point
Global energy-related CO₂ emissions in 2050 must be half of current levels to limit the global temperature increase to 2°C.

Source: IEA Energy Technology Perspectives (2012)
MEETING 2050 GHG REDUCTION GOALS =>
FUEL MIX WITH > 50% BIOFUELS + ELECTRICITY + H2

Figure 7.15 Fuel demand by fuel type

Key point: Compared to the 4DS, total road vehicle fuel demand in all 2DS variants is almost halved and much more diversified by 2050.

Source: IEA Energy Technology Perspectives (2012)
MEETING 2050 GHG REDUCTION GOALS =>
LIGHT DUTY SECTOR W/ MAJOR USE OF ELEC. DRIVE (Hybrid, Plug-in electric & H2 Fuel Cell)

Key point: In the Improve case, electric, PHEV and FCEVs together account for nearly three-quarters of new vehicle sales in 2050.

Source: IEA Energy Technology Perspectives (2012)
TRENDS FOR SUSTAINABLE TRANSPORTATION

• A revolution in transport technology/fuels will be required to meet GHG goals
  ▪ New types of vehicles
  ▪ New infrastructure
  ▪ Low carbon primary supply

• Each solution faces non-trivial technical, economic, policy, political, and market challenges toward full commercialization

• WHAT IS CURRENT STATUS OF ALT FUELS AND VEHICLES?

• HOW DO WE MAKE A TRANSITION?
STEPS Program Overview

Dr. Joan Ogden, Director

Dr. Dan Sperling, Co-Director

Dr. Lew Fulton, Co-Director

Paul Gruber, Manager

www.steps.ucdavis.edu
ITS-Davis research consortia continue to evolve to consider more complex alternative fuel/vehicle transition questions

**GOAL:** Generate visions of the future grounded in technical and economic realities, a strong knowledge base for companies making long-term technology investments, and sophisticated analyses of future policies.
STEPS Program Outputs (2007-present)

• RESEARCH
  ▪ Research papers (journals, conferences, tech. reports)
  ▪ Sponsors’ workshops on research
  ▪ White papers (key research results)

• OUTREACH/POLICY ENGAGEMENT
  ▪ Service on CA, US, international panels, committees
  ▪ Policymakers’ briefings and workshops
  ▪ Testimony

• EDUCATION
  ▪ 25 Graduate degrees by end of 2011 (mostly Ph.D. level); courses taught
# UC Davis
Sustainable Transportation Energy Pathways (STEPS)
*Single Pathway Analyses and Comparisons*

**2007-2010**

<table>
<thead>
<tr>
<th>Hydrogen</th>
<th>Biofuels</th>
<th>Electricity</th>
<th>Fossil Fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell Vehicles</td>
<td>Bio-ICE Vehicles</td>
<td>Battery-electric Plug-in hybrids</td>
<td>Bus. as usual Low-carbon fuels (incl. CCS)</td>
</tr>
</tbody>
</table>

- **Consumer Demand & Behavior**
- **Infrastructure Modeling**
- **Vehicle Technology Evaluation**
- **Energy, Environmental & Economic Cost Analysis**
- **Scenarios & Transition Strategies**
- **Policy & Business Decisions**
NextSTEPS analysis draws on wide range of ITS & UC Davis research

- **PH&EV Center** (PEV modeling, consumer surveys)
- **China Center** (consumers, infrastructure)
- **ULTRANS** (VMT, mobility)
- **Energy Institute** (biofuels)
- **Policy Institute** (energy, econ., env. policy analysis)
- **Contracts** (NETL, NREL, CEC, CARB, Industry)

NextSTEPS (pathway comparisons, scenarios, transition strategies)
Major Learning from STEPS: a portfolio approach is needed

Most important insight from STEPS research: a **portfolio approach** combining efficiency, alt fuels and VMT reduction will give us the best chance of meeting stringent goals for a sustainable transportation future.

Given the uncertainties, and the long timelines, it is critical to nurture a portfolio of key technologies toward commercialization and to start now.

All our work in characterizing pathways and comparing them flows toward this conclusion.

**FREE DOWNLOAD**

http://steps.ucdavis.edu/research/steps-book/
NextSTEPS Program Research Highlights
Plug-in Electric Vehicles

With thanks to Dr. Tom Turrentine and Dr. Mike Nicholas

University of California, Davis
## Plug-In Vehicles

<table>
<thead>
<tr>
<th></th>
<th>Plug-in Prius</th>
<th>Chevy Volt</th>
<th>Nissan LEAF</th>
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</thead>
<tbody>
<tr>
<td><strong>Battery kWh:</strong></td>
<td>4 kWh</td>
<td>16 kWh</td>
<td>24 kWh</td>
</tr>
<tr>
<td><strong>Charge Time:</strong></td>
<td>3hrs/110v (15A)</td>
<td>10hrs/110v(15A)</td>
<td>20hrs/110v(20A), 8hrs/220v(40A), .5hrs/480v(80A)</td>
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<tr>
<td></td>
<td>1.5hrs/220v(3A)</td>
<td>4hrs/220V(30A)</td>
<td>80% SOC</td>
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<tr>
<td><strong>All Electric Range:</strong></td>
<td>20 km</td>
<td>60 km</td>
<td>160 km EPA 110 km</td>
</tr>
<tr>
<td><strong>Price:</strong></td>
<td>Base $30,500-$40,000</td>
<td>Base $41,000</td>
<td>Base $33,720</td>
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</table>
CONSUMER ACCEPTANCE OF BATTERY VEHICLES IS KEY ISSUE

PEVs radical departure from today’s vehicles in terms of efficiency (3 to 4 times that of a conventional gasoline vehicle), range (currently about 150-200 km), utility, flexibility, and the refuelling experience (home charging typically takes several hours).

Battery costs are still high, but are projected to come down.
CAN HYBRID EV (HEV) HISTORY OFFER INSIGHTS ABOUT PEV FUTURE? (6.8 MILLION HEVS IN WORLD)

**Japan**: HEV sales reached 20% in 2013, Aqua and Prius top selling vehicles: 2 million registered

**California**: 10% 3\(^{rd}\) quarter of 2013, Prius best selling vehicle in 2012-13 (60,000)

**USA**: 3.5% first half 2013, 2.9 million registered
PEVs: ARE THEY FOLLOWING PATH OF HEVs?

US HEVs (2 yrs from launch)

Note: Approximation assumes CA sales were 60% of U.S. sales in 2011 and 33% in 2012 and 2013. Reference: www.hybridcars.com

4/5/2013
Most PEV household lease the car maybe because it is a new technology.

- Lease is used by all income groups
- Leases may reflect the OEM policy & the consumer preference
- Many leases up soon, will create a used PEV market soon…
Electricity system is capable of sustaining vehicles for decades. If PEV adoption is concentrated in certain regions, this could require upgrades to distribution infrastructure, but there may not be a need for additional generating capacity in the near term.

GHG benefits of PEVs depend on source of electricity. Need to decarbonize the grid to get full benefit.

Battery storage potentially important for vehicles, grid.

Over the long term demands for electric vehicles could be part of a future electricity system that incorporates intermittent renewables in a “smart grid”.
A million PEVs charging at night is only about 1% of the California grid.
GHG benefits of PEVs depend on elec. source (PHEVs~ HEVs for current US grid) (MIT).
Plug-in Electric Vehicle Pathway: Take Away Messages

• PEVs offer major potential for GHG reduction and oil displacement.
• PEVs represent a radical departure from conventional vehicles wrt efficiency, range and refuelling. Thus, consumer acceptance of battery vehicles is a key to their future success.
• Costs and performance of batteries are a key issue for adoption of electric vehicles. Although the costs are coming down and performance is improving, the technology is still expensive for use in passenger vehicles.
• Automakers are making major commitments to Plug-in Hybrid EVs (PHEVs) and Battery Electric Vehicles (BEVs), and models are entering the market.
• Electricity is already in widespread use by consumers, so building EV infrastructure is largely focused on the point of refuelling—the vehicle charger.
• Most drivers of plug-in electric vehicles (PEVs) will recharge primarily at home or work. However, some level of public access to charging is probably needed to overcome the range limitations of pure battery electric vehicles (BEVs), and because many drivers do not have access to overnight off-street parking.
• Even with significant penetration of BEVs and PHEVs in the next few decades, electricity demand for recharging these vehicles will make only a minor contribution to total electricity demands.
• Although PEVs have zero tailpipe emissions, the well to wheel environmental benefits of PEVs depend on the type of electricity supply. To realize potential GHG benefits of PEVs it is necessary to substantially decarbonize the electricity supply over time by incorporating renewables and fossil electricity with carbon capture and sequestration.
Hydrogen and Fuel Cell Vehicles
FUEL CELLS: BETTER ROUTE -> ELECTRIC CAR?

H₂ fuel cell vehicles have zero tailpipe emissions, high efficiency, good performance, fast refueling.

Several hundred experimental H₂ Fuel Cell vehicles worldwide; automakers see commercial readiness ~ 2015-2020.

Source: http://www.h2cars.de/
Automakers see H2 FCVs + Battery EVs

How a H₂ Fuel Cell Works
H₂ SUPPLY PATHWAYS

Like electricity, hydrogen is an energy carrier that can be produced from widely available primary energy resources.
Challenges: Technical Status (1)
H2 FCVs rapidly approaching technology goals.
Challenges: Building H2 Infrastructure

What Will a H2 Infrastructure Look Like?

On-site H₂ production

Existing energy infrastructure

Central H₂ production

CO₂ capture & storage

Central H₂ Plant

Plant to city-gate transmission

Local distribution network
Challenges: Building H2 Infrastructure

Improved strategies for early H2 networks

Vehicles placed by population

Cluster strategy:
Co-locate early FCVs and H2 stations in a few cities in region

H2 Pathways CA H2 Highway Network Study 2005:
Ave. travel time to 17 optimally placed stations in LA Basin
= 16 minutes

UCD H2 Rollout Study 2010:
Ave. travel time to 16 optimally placed stations in LA Basin
= 4 minutes

Challenges: Building H2 Infrastructure

Early H2 costs high, but fall with increased scale to $3-4/gge

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<td>Nashville, Buffalo, Raleigh</td>
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<td>Nationwide</td>
<td>260</td>
<td>540</td>
<td>720</td>
<td>900</td>
<td>1180</td>
<td>1460</td>
<td>1740</td>
<td>1920</td>
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<td>2280</td>
<td>2460</td>
<td>2640</td>
<td>2820</td>
<td>3000</td>
</tr>
</tbody>
</table>

US Scenario for FCV rollout and H2 cost v. time

H2/FCV Pathway: Take Away Messages

- H2 FCV technologies progressing rapidly, could be commercially ready c. 2015. H2 infrastructure build-out is currently rate limiting factor.
- H2 FCV rollout plans in Germany, Norway, Japan, Korea, USA.
- Many low-C pathways available for future H2 supply. In the long term, H2 could cost $3-4/gge, competing with gasoline at $2-3/gge on a cents/mile basis.
- Major “ancillary benefits” w/H2 FCV in addition to GHG, oil reduction
- Early infrastructure “cluster” strategies => sparse station networks w/good fuel access, relatively low cost, possible business case >2020
- H2 FCVs could play major role in Light Duty Vehicle markets, but realizing this will require strong stakeholder coordination and policy.

H2 FCVs is key part of portfolio approach to deep cuts in GHG emissions & oil use, that includes efficiency, biofuels, electric drive.
Biofuels

With thanks to Dr. Nathan Parker

University of California, Davis
Challenges on the Biofuel Pathway

• **Sustainability challenges.** Biofuels at large scale would place large demands on scarce land and water resources.

• **Technical challenges.** Time is needed to develop and demonstrate cellulosic biofuel technologies at commercial scale.

• **Logistical challenges.** Alcohol fuels face limited market without large scale deployment and consumer acceptance of E85 in flexible-fuel vehicles.

• **Policy challenges.** Policies need to be crafted that encourage investment in cellulosic biofuels that are sensitive to the sustainability challenges.
Sustainability Challenges

- Crop-based biofuels that could compete with petroleum fuels pose large demands on the global agricultural base leading to potentially undesirable impacts:
  - increased food prices (global equity issues),
  - expansion of cultivated lands (carbon releases, habitat loss), and
  - intensification (fertilizer and pesticide, increased monocultures).
- Residue based biofuels can also be consumed at unsustainable rates with impacts on long term soil quality and ecosystem health.
UC Davis research on future biofuel supply

- Spatial supply chain optimization model to project future biofuel supplies

- A wide range of feedstock scenarios and technology scenarios have been considered for the 2018 to 2022 timeframe.
Biofuels could supply 6.5% to 22% of total US Light Duty Vehicle fuel demand in 2018

- Estimates for total sustainably available biofuels vary widely.
- At $3/gge-$4/gge
  - 2-10% from wastes and residues
  - 0-7% from energy crops and pulpwood
  - 1-5.5% from corn and soy
A simulated industry to meet the US Renewable Fuel Standard (RFS)

- To achieve federal mandated volumes:
  - 200 to 250 commercial scale cellulosic biorefineries needed, costing $100-360 Billion.
  - Corn ethanol and cellulosic biofuels from MSW and forest residues are the low cost pathways
Resource Consumption by Biorefineries
Biofuel Compatibility with Existing Infrastructure

Current liquid **biofuels** such as ethanol are at least partly compatible with existing petroleum infrastructure, in that they can be **blended** with petroleum-based fuels at concentrations of up to 10-20% without infrastructure changes.

With future “**drop-in**” **biofuels** produced from cellulosic materials via gasification and Fischer-Tropsch synthesis, might be possible to use petroleum storage, pipeline system & terminals.

**Biofuels** can be used in today’s flex-fuel internal combustion engine vehicles, and should be transparent to the consumer in terms of performance.
Biofuel Pathway: Take Away Messages

• Biofuels can be blended with gasoline or diesel and used in existing vehicles, which eases their introduction into the transportation system. “Drop-in” biofuels can be compatible with existing petroleum infrastructure. Liquid biofuels have an advantage in serving sectors such as aviation and freight that require easily transportable, energy-dense fuels.

• Costs/benefits of biofuels vary greatly, depending on pathway. With current biofuels production technology (ethanol from sugar or starch, biomethane, and biodiesel), the lowest-cost biofuels do not provide major environmental benefits. Advanced biofuels now under development (cellulosic ethanol or diesel from biowastes, bio-oils from algae) could have significant environmental benefits.

• The first commercial-scale biorefineries are expected to produce large quantities of advanced biofuels c. 2015. Adv. biofuels are expected to have small GHG footprints, but can face some of the same indirect land-use change challenges as conventional biofuels if cultivating their feedstocks displaces food crops.

• Biofuels raise a host of sustainability questions (GHG emissions, land use, water use) and macroeconomic issues (competition for land used in agriculture). Balancing sustainability with increasing biofuel production requires the consideration of many factors. Capturing all these factors within a policy and regulatory framework will be challenging.

• Ultimately biofuels will be limited to perhaps 10-20% of transport fuel energy.
Advanced Fossil Pathways

With thanks to Amy Myers Jaffe and Lew Fulton

University of California, Davis
OIL SUPPLY CURVE: PLENTY OF OIL, BUT HIGH COST, CARBON EMISSIONS
Numerous Shale Plays in United States

Shale resources widely spread across the continent
U.S. Natural Gas Production Outlook

Shale will be 50% of U.S. production by 2020 vs. 37% today
Wide gap between wholesale diesel and Henry Hub natural gas prices
Global NGV evolution

Source: NGVA-Europe

MILLIONS OF ??

2003 2004 2005 2006 2007 2008 2010

NORTH AMERICA
AFRICA
RUSSIA & C.I.S.
EUROPE
MIDDLE EAST
LATIN AMERICA
ASIA PACIFIC
NG FOR TRUCKING

UC Davis NG Supply Chain Model (Jaffe et al.)

1) Identify if the build-out of LNG and CNG supply chains are sustainable as a commercially profitable venture in the United States and if so, what is the most cost-effective supply chain configuration of LNG infrastructure, based:

2) Identify important, profitable routes which will support future network growth

2 LNG Pathways
LNG FOR TRUCKING: KEY CONCLUSION
Launch scenarios at <1% of heavy trucking fueling market share (today’s market even incl. Clean Energy network is a fraction of that) is unlikely to be sufficient as a sustainable commercial base. May need 10%
COMPARING PATHWAYS: ISSUES FOR FUTURE TRANSPORTATION FUELS

• Consumer Acceptance
• Technical Status and Prospects: Vehicles and Fuels
• Infrastructure/Logistics
• Economics
• Resources
• Environment/Sustainability
• Transition dynamics
<table>
<thead>
<tr>
<th>Hydrogen</th>
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<tr>
<td>Consumer acceptance</td>
<td>Cost of H2 FCVs; early fuel availability</td>
<td>Veh. ~ gasoline/diesel; food/fuel/land issues</td>
</tr>
<tr>
<td>Tech Status: Vehicle</td>
<td>FCVs demo; Commercial c.2015; (Fuel cells/H2 sto.)</td>
<td>Pre-commercial PHEVs and EVs; (batteries)</td>
</tr>
<tr>
<td>(critical Tech)</td>
<td>Large scale fossil H₂ commercial; Low-C. H₂ production</td>
<td>Commercial vehicles similar to gasoline veh.</td>
</tr>
<tr>
<td>Tech Status: Fuel</td>
<td>Elec. system exists, but need decarbonized grid. Low-C. elec generation</td>
<td>1ˢᵗ gen biofuels from starch, sugar crops 2ⁿᵈ gen. biorefinery</td>
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<td>Infrastructure</td>
<td>New infrastructure needed (mature H2 infrastructure $1400-2000/car)</td>
<td>New in-home (cost $1000-2000/car) and public chargers, upgrade T&amp;D</td>
</tr>
<tr>
<td>Economics (mature tech., full scale)</td>
<td>H2 FCV $3600-6000 &gt; gasoline ICEV; H2 delivered $3-4/gge</td>
<td>$5000 (PHEV) to $15000 (EV) &gt; gasoline ICEV</td>
</tr>
<tr>
<td>Resources</td>
<td>Diverse resources for H₂ production, huge low-Carbon resource base</td>
<td>Diverse resources for electricity production, huge low-Carbon resource base</td>
</tr>
<tr>
<td>Environmental Impacts/oil use</td>
<td>H2 Pathway dependent</td>
<td>Electricity Pathway dependent</td>
</tr>
<tr>
<td>Transitions (time, cost to breakeven)</td>
<td>Requires stakeholder coordination, policy 10-20 yr ($10s-100sB)</td>
<td>Veh adoption determines transition time 10-20 yr ($10s-100sB)</td>
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<td>H2 Pathway dependent many low-impact options</td>
<td>Elec. Pathway dependent many low impact options</td>
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<tr>
<td><strong>Transitions</strong></td>
<td>Requires stakeholder coordination, policy 10-20 yr ($10s-100sB)</td>
<td>Veh adoption determines transition time 10-20 yr ($10s-100sB)</td>
</tr>
</tbody>
</table>
COMPARING PATHWAYS:
NO DEFINITIVE WINNER

EACH PATHWAY HAS DIFFERENT CHALLENGES

NO SINGLE PATHWAY CAN MEET ALL GOALS

PORTFOLIO APPROACH combining efficiency, alt fuels and travel reduction may give the best chance of meeting stringent goals for sustainable transportation future.

HOW DO WE ACCOMPLISH THESE TRANSITIONS AND WHAT INVESTMENTS ARE NEEDED?
VEHICLE COMMERCIALIZATION TIMELINE

Source: Cunningham, Gronich and Nicholas, presented at the NHA Meeting, March 2008.
REFUELING STATIONS FOR GASOLINE & ALTERNATIVE FUELS

Gasoline

CNG

Ethanol

Methanol

~100+ H₂ refueling stations worldwide
HISTORICAL DATA: MAJOR US TRANSPORTATION INFRASTRUCTURES

time constants: 30-70 years

FIGURE 3.8 Penetration of major U.S. transportation infrastructures. SOURCE: Adapted from Marchetti (1985); Ausubel (1996).
STEPS Scenario for Fleet Mix to 2030 (1000s vehicles on road – US)
Incremental Alt. Vehicle Costs and Fuel Savings ($billion/y): Breakeven c. 2027

- PHEV
- EV
- FCV

# at top of each bar is net cost $billion/y
TRANSITION COSTS

• Our simple “portfolio” scenario breaks even ~2025.

• Beyond this, fuel savings outweigh incremental costs for vehicles.

• Investments to breakeven are $10s-100 B, the majority for vehicles.

• Infrastructure costs to break even are in the $5-20B range (depending on the fuel).

• Of course, the results are sensitive to a lot of assumptions (see extra slides in Appendix).

IS THIS A LOT OF MONEY?
In the US we will spend around $15 trillion on new cars and fuels through 2030

Source: EIA/AEO 2012
NRC 2013 “iconic figure”: Subsidies account for around $40B, 2015-2030, but societal benefits are far greater.
STEPS 3 (2015-2018): Key Research Areas for the Transition to Sustainable Transportation

1. Initiating Transitions 2015-2030
   *What is required for early alt. fuel/vehicle transitions to succeed?*

2. The Future of Fuels and the Oil Industry
   *How will abundant fossil fuels affect the future mix of fuels?*

3. The Future of Global Urban Sustainable Transport (GUSTO)
   *How will a rapidly urbanizing world affect transport and energy demand?*

4. Modeling Analysis, Verification, Regulatory and International Comparisons (MAVRIC)
   *What do improved and intercompared transportation/energy models tell us?*