Global Population Density 1995 (persons per km$^2$)
Earth’s Cities at Night
CHALLENGES FACING FUTURE ENERGY SYSTEM

- Growth of demand, esp. in developing countries
- Diversity/Security of Energy Supply, esp. in transportation sector
- Air Pollutant Emissions
- Greenhouse Gas Emissions (GHG)
- Water, land, materials constraints
FUEL SECTOR IS IMPORTANT

• Direct combustion of fuels for transportation and heating accounts for about 2/3 of primary energy use and GHG emissions, and a large fraction of air pollutant emissions.

• World transportation sector 97% dependent on oil.

• # vehicles projected to triple worldwide by 2050

• In US, ~28% of GHG emissions are from transportation (CA ~40%; 20% worldwide); transportation is rapidly growing GHG source in the US and globally.
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)

---

A comprehensive energy strategy should have a “portfolio” approach with multiple solutions
STABILIZATION WEDGES (Pacala, Socolow)

ANNUAL EMISSIONS
In between the two emissions paths is the “stabilization triangle.” It represents the total emissions cut that climate-friendly technologies must achieve in the coming 50 years.

- Historic
- Delay action until 2056
- Begin action now
- Stabilization triangle

CA 2050 GHG Goal:
80% below 1990 level
Doubling vehicle efficiency could become one “wedge”, zero-carbon fuels another
POTENTIAL FOR VEHICLE ENERGY EFFICIENCY (ICEVS 2X +)

REDUCING VMT

“Recent studies show that substantial reductions in travel and emissions of pollutants and greenhouse gases are possible (10%-30%, compared to the future base case), but only with combined transportation investment, land use, and travel pricing policies.”

POTENTIAL FOR ALTERNATIVE FUELS

• Growing imperative for alternative fuels
  ▪ Oil supply security
  ▪ Climate Change

• Search for solutions by policymakers, industry
  ▪ Innovative Policy Landscape

• Continuing tech progress in variety of alt fuel and vehicle technologies
  ▪ Biofuels
  ▪ Electricity (Plug-in Hybrid vehicles, Battery vehicles)
  ▪ H2/Fuel Cell Vehicles
  ▪ Fossil-based fuels w/Carbon Capture and Sequestration
History of alternative fuel vehicles (US)

All Vehicles and Alt Fuel Vehicles

Year

# vehicles (1000s)

Will the future be different? MAYBE..
History of alternative fuel vehicles (US)

Alternative Fueled Vehicles (1000s)

References: Davis, Transportation Energy Data Book (2008)
VEHICLE COMMERCIALIZATION TAKES TIME

Source: Cunningham, Gronich and Nicholas, presented at the NHA Meeting, March 2008.
INTRODUCING INNOVATIONS IN VEHICLES
time constants: 20-60 years

Figure 60: Market penetration rates of different vehicle technologies. Source: Automatic transmission penetration data from EPA [2006a]; Diesel penetration data from ACEA [2007].
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).
TRANSITIONS TAKE TIME

• Tech and cost issues for key technologies
  ▪ Fuel cells
  ▪ Advanced batteries
  ▪ Low-C fuel conversion pathways (Biofuels, renewables, fossil w/Carbon Capture and Sequestration)

• Market adoption of vehicle innovations
  ▪ Historically, 20-60 years from R&D to >35% of fleet

• Building new transportation infrastructure
  ▪ Historically, 30-70 years

• Policy driving major change (>10 years?)
UC Davis STEPS Program Overview
GOAL:
Conduct robust comparisons of different fuel / vehicle pathways

RESEARCH       EDUCATION       OUTREACH

www.steps.its.ucdavis.edu
STEPS Program Goals & Objectives

• The overarching goal of the program

  The development & application of tools and methods that allow for robust comparisons of different fuel / vehicle pathways.

• The objectives of the program include

  ▪ Comparative analysis research. Conduct interdisciplinary research on multiple pathways
  ▪ Knowledge dissemination. Communicate research to sponsors, scientific community, and policy makers
  ▪ Education. Educate next generation of engineers, scientists, business and policy decision-makers
Program Numbers

- Sponsors: 19 (13 industry, 6 gov)
- Faculty & researchers: 15
- Graduate Students: 25 (22 PhD, 3 MS)
- Collaborating departments:
  Environmental Science & Policy, Civil Engineering, Biological & Agricultural Engineering, Mechanical and Aeronautical Engineering, Economics, Agriculture & Resource Economics, Plant Sciences
Program Outputs (2007-2010)

• 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
  ▪ 20 Graduate degrees by end of 2010 (mostly Ph.D. level); courses taught
20 Graduate Degrees Granted (2007-2010)

- Jonathan Weinert, Ph.D. TTP (Chevron)
- Gustavo Collantes, Ph.D. TTP (State of Washington)
- Brett Williams, Ph.D. TTP (UC Berkeley)
- Reid Heffner, Ph.D. TTP (Booz Allen Hamilton)
- Jonn Axsen, Ph.D. TTP (ITS Post-Doc)
- Nic Lutsey, Ph.D. TTP (ICCT)
- Guihua Wang, M.S. Ag. & Resource Econ.; Ph.D. Civil & Environmental Eng. (CARB)
- Zhenhong Lin, Ph.D. Civil & Environmental Eng. (ORNL)
- Jonathan Hughes, Ph.D. TTP (CU Boulder, Econ. Dept.)
- Ryan McCarthy, Ph.D. Civil & Environmental Eng. (CCST Fellowship)
- Michael Nicholas, Ph.D. TTP (Post-Doc ITS-Davis)
- Nathan Parker, M.S. TTP (Ph.D. candidate TTP)
- Joel Bremson, M.S. TTP (Ph.D. candidate TTP)
- Brent Riffel, M.S. TTP (Lifecycle Assoc.)
- Wayne Leighty, M.S. TTP; M.S. Ag. & Resource Econ.; MBA; Ph.D. TTP (Shell)
- David McCollum, M.S. TTP; M.S. Ag. & Resource Econ.; Ph.D. TTP (IIASA)
- Yongling Sun, M.S. Ag. & Resource Econ.; Ph.D. TTP (Post-doc at ITS-Davis)
- Ryohei Hinokuma, M.S. TTP (SF Community Power)
- Obadiah Bartholomy, M.S. TTP (SMUD)
- Eric Huang, Ph.D. Civil & Environmental Eng. (UC Davis)
Publications and Awards (2007-2010)

Publications: 100 +  (full list at www.steps.its.ucdavis.edu)

Awards:
2010:  Heinz award: Dan Sperling
2009 Johannes Linneborn Prize for outstanding contributions to the development of energy from biomass  
(Prof. Bryan Jenkins)
2009 Kinsella Memorial Prize (Dr. Nicholas Lutsey)
2009-10 Achievement Rewards for College Scientists (ARCS) (David McCollum)
2009 Dwight David Eisenhower Graduate Fellowships (Geoff Morrison, David McCollum)
2008 Barry McNutt Award for Best Paper on Energy, Transportation Research Board (Prof. Chris Knittel, Jon Hughes, Prof. Dan Sperling)
2008 UC Davis Chancellor’s Fellow Award (Prof. Chris Knittel)
2008 Women's Transportation Society Helene M. Overly Memorial Graduate Scholarship (Xuping Li)
2008 Friends of ITS-Davis Outstanding Master's Thesis (Wayne Leighty)
2008 Friends of ITS-Davis Outstanding Dissertation Award (Nicholas Lutsey)
2007 Barry McNutt Award for Best Paper on Energy, TRB (Michael Nicholas, Prof. Joan Ogden)
2007 Best Paper from the Scientific Committee of the 2nd World Congress of Young Scientists on Hydrogen Energy Systems (Dr. Zhenhong Lin)
2007 ITS-Davis Outstanding Master’s Thesis Award (David McCollum)
2007 University of California, Davis Distinguished Scholarly Public Service Award (Prof. Joan Ogden)
2007 Charley V. Wootan National Student Award for best Master’s Thesis in Transportation Policy and Planning (Nathan Parker)
Portion of 2007 Nobel Peace Prize for his contributions to UN’s Fourth IPCC Report (Prof. Dan Sperling)
2007 UC Davis Sustainable Transportation Center’s “Outstanding Student of the Year” (Jonathan Weinert)
STEPS Program Events (2007-2010)

• Policymaker Briefing, Washington DC 1/23/2007
• Research Symposium, UC Davis 5/21–22/2007
• Advisory Board Meeting, Asilomar 8/21/2007
• Policymaker Briefing, Sacramento 10/15/2007
• CARB/ITS-Davis Vehicle GHG Workshop, Sac 4/21/2008
• Research Symposium, UC Davis 5/13–14/2008
• Policymaker Briefing, Washington DC 1/12/2009
• Policy Symposium, UC Davis 3/10–11/2009
• Advisory Board Meeting, Asilomar 7/28/2009
• Research Symposium, UC Davis 5/14-15/2010
STEPS Research Informs the Policy Process

US NATIONAL

• Prof. Dan Sperling – NRC/NAS committees on Transport and Climate, and Energy Efficiency.
• Prof. Dan Sperling - American Physical Society Committee on Energy Efficiency
• Prof. Dan Sperling – US Congressional testimony on LCFS
• Prof. Joan Ogden – NRC/NAS committees for H2 & Fuel Cells (2007-8) and PHEVs (2009-2010).
• Prof. Joan Ogden – US Department of Energy, Hydrogen Technical Advisory Committee

INTERNATIONAL

• Prof. Dan Sperling - Chair, Global Agenda Council on the Future of Mobility, World Economic Forum, Davos, Switzerland
• Prof. Joan Ogden – Lead Author, IPCC Committee Special report on Renewable Energy (2009-2010)
STEPS Research Informs the Policy Process

STATE OF CALIFORNIA AND WESTERN REGION

- Prof. Dan Sperling leads UC Davis team on UC Low Carbon Fuel Standard reports. 7 STEPS researchers contribute to reports.
- Prof. Dan Sperling, Prof Joan Ogden, Dr. Christopher Yang, California Commission on Science and Technology, California Energy Future Study 2009.
- Prof. Bryan Jenkins, Nathan Parker - Western Governor’s Association report on biofuels
- Prof. Bryan Jenkins - advisor to state on biomass energy and renewable energy
- Prof. Joan Ogden – CARB Economic and Technical advisory panel for AB32
- Prof. Chris Knittel - CARB Economic and Allocation Advisory Committee for AB32 (GHG law)
- Prof. Chris Knittel - Part of UCD/UCB team developing rec.s for CA “feebate” program
- Prof. Chris Knittel - Part of UCD/UCB team developing rec.s for CA LCFS
- Prof. Cynthia Lin appointed to CA state economic advisory group
- Dr. Sonia Yeh, Dr. Nic Lutsey, modeling for CA LCFS implementation

AD HOC ADVICE TO CARB AND CEC ON A WIDE VARIETY OF ALTERNATIVE FUEL AND VEHICLE ISSUES
Purpose: Illuminate role of alternative fuels and vehicles in a sustainable transportation future, based on insights from the UC Davis STEPS program.

Audience: Decision-makers in government and industry; graduate students/professionals in energy/environment/transportation.

Format: 16 chapters, written at “Scientific American” level, based on the many ground-breaking studies that have emerged from STEPS.

Timeline: Jan. 2011: Near-final draft → sponsors
**Purpose:**
Illuminate role of alternative fuels and vehicles in a sustainable transportation future, based on insights from the UC Davis STEPS program

**Audience:**
Decision-makers in government and industry; graduate students/professionals in energy/environment/transportation

**Format:**
15 chapters, written at "Scientific American" level, based on the many ground-breaking studies that have emerged from STEPS.
STEPS Research Questions

What do individual fuel/vehicle pathways look like?

How do these pathways compare?

How could we combine pathways and approaches to meet societal goals for carbon reduction, energy security, and other sustainability goals?

What policy measures are needed to progress toward sustainable transportation systems?
Understanding Single Pathways

• Multiple Challenges
  ▪ Introduce new types of vehicles
  ▪ Modify existing or build new fuel infrastructures
  ▪ Develop low carbon primary supply

• Different fuel/vehicle pathways face different challenges

• Implementing any pathway takes time
Source: Cunningham, Gronich and Nicholas, presented at the NHA Meeting, March 2008.
Comparing Pathways

**GOAL:**
Conduct robust comparisons of different fuel / vehicle pathways

**Project Areas:**
- Consumer Behavior
- Infrastructure
- Lifecycle Analysis
- Policy
- Vehicle Technology

**HYDROGEN**
- Fuel Cell Vehicles
- H2-ICE Vehicles

**BIOFUELS**
- Bio-ICE Vehicles
- 2\textsuperscript{nd} Gen Biofuels

**ELECTRICITY**
- Battery-electric
- Plug-in hybrids

**FOSSIL FUELS**
- Business as usual
- Low-carbon fuels (incl. CCS)
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<th>Hydrogen</th>
<th>Electricity</th>
<th>Biofuels</th>
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<td><strong>Consumer acceptance</strong></td>
<td>Cost of H2 FCVs; early fuel availability</td>
<td>Cost of EVs; recharge time &amp; place /range</td>
<td>Veh. ~ gasoline/diesel; food/fuel/land issues</td>
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<td><strong>Tech Status: Vehicle (critical Tech)</strong></td>
<td>FCVs demo; Commercial c.2015; (Fuel cells/H2 sto.)</td>
<td>Pre-commercial PHEVs and EVs; (batteries)</td>
<td>Commercial vehicles similar to gasoline veh.</td>
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<td><strong>Tech Status: Fuel (critical Tech)</strong></td>
<td>Large scale fossil H$_2$ commercial; Low-C. H$_2$ production</td>
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<td><strong>Infrastructure</strong></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>
<td>EtOH partly compatible w/petroleum infra (“drop-in fuels” fully compatible)</td>
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<td><strong>Economics (mature tech., full scale)</strong></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>
<td>Biorefineries are primary infra. cost; Biofuel for 10-20% demand &lt; $3-4/gge</td>
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<td><strong>Resources</strong></td>
<td>Diverse resources for H$_2$ production, huge low-Carbon resource base</td>
<td>Diverse resources for electricity production, huge low-Carbon resource base</td>
<td>Limits on providing enough low cost biofuels for all transportation</td>
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<td><strong>Environmental Impacts/oil use</strong></td>
<td>H2 Pathway dependent</td>
<td>Electricity Pathway dependent</td>
<td>Biofuel Pathway dependent</td>
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<td><strong>Transitions (time, cost to breakeven)</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>
<td>Biorefinery build-out determines transition time. RFS 2022 $100sB</td>
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<td><strong>Environmental</strong></td>
<td>H₂ Pathway dependent many low-impact options</td>
<td>Elec. Pathway dependent many low impact options</td>
<td>Biofuel Pathway dependent</td>
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</table>
Comparing pathways: No definitive winner

EACH PATHWAY HAS DIFFERENT CHALLENGES

- **Biofuels** require few/no vehicle changes, can be compatible w/ existing infra (w/ drop-in fuels); face limits to resource availability, and uncertainties wrt land use, GHG, sustainability.

- **H₂** => new infrastructure, stakeholder coordination & policy during rollout, new vehicle (FCV costs $3.6-6K> gasoline car). Fast refuel, >300 mi range. Large potential benefits wrt GHGs, air pollutants, oil displacement; huge low carbon resource base.

- **Electricity** requires home chargers (which can be built as needed) as part of larger electric power system; new vehicle types (EVs, PHEVs cost more $5-15K>gasoline), different range/charging characteristics from gasoline. Large potential benefits wrt GHGs, air pollutants, oil displacement; huge low carbon resource base.

NO SINGLE PATHWAY CAN MEET ALL GOALS
Perhaps the single most important insight from STEPS research is that a **portfolio approach** 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.
NextSTEPS: new 4 year consortium that builds on knowledge and tools developed under STEPS
New tools to assess Bio-Fuel Pathways (CA, Western U.S., National U.S.)

Engineering/Economic Models of Biorefineries

Spatially Explicit Resource Assessment

GIS-based Transportation Cost Model

Supply Chain Optimization Model

Bioenergy Supply Curves

Spatially Explicit Refinery Optimization
Optimal System design cellulosic ethanol ⇒ Large bio-refineries + signif. feedstock transport distance

Median Feedstock transport distance ~ 70 mi; 25% of feedstock transported >100 mi
National Biorefinery Siting Model for the US: Biorefinery Locations
Biomass Deliveries

Biomass feedstocks transported at $2.50/gge

[Map showing biomass feedstock transportation across the United States with different tonnage categories represented by different colors.]
Total US Biofuel supply curve

RFS2 2017 Target
(24 billion gallons ethanol equivalent)

RFS2 2022 Target
(36 billion gallons ethanol-equivalent)
Pathway Comparison: H2 FCV vs. PHEV

TRANSITION TIMING, COSTS SIMILAR

PHEV enters market sooner & at lower price, but learned-out price could be less for FCV.

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<tr>
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<th>PHEV</th>
<th>FCV</th>
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<tr>
<td>Breakeven Year</td>
<td>2020-2026</td>
<td>2023-2032</td>
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<tr>
<td>Cumulative vehicle price difference to breakeven</td>
<td>$26-174 Billion</td>
<td>$40-91 Billion</td>
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<td>$7000-9000/car</td>
<td>$7000-9000/car</td>
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<tr>
<td># cars at breakeven yr</td>
<td>4-20 million</td>
<td>5.6-10 million</td>
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<td>Infrastructure cost</td>
<td>$3-40 Billion</td>
<td>$8-19 Billion</td>
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<td>($800-2000/car for residential charging)</td>
<td>($1400-2000/car for full infrastructure)</td>
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</table>
Advanced vehicles and fuels will have important impacts on the electric sector.
## Finding the “Greenest” Time to Plug into CA Grid c.2010

Today Greenest = Winter, Nighttime (R. McCarthy)

### Average hourly marginal generation GHG emissions rate (gCO₂-eq/kWh)

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<tr>
<th>Hour</th>
<th>Avg. recharging demand (MW)</th>
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**Demand-weighted avg.:** 647 601 629 590 580 617 639 665 640 640 613 650 626
Green Charging w/future low-Carbon grids
Tech choice ⇒ greenest time of day (R. McCarthy)

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- **Wind-heavy** ⇒ nighttime green charging
- **Solar-heavy** ⇒ daytime green charging
- **Wind/solar** ⇒ anytime green charging
Analysis of transportation options for meeting stringent GHG emission goals (CA, US)

What constitutes a scenario?

- What vehicle technologies are used?
- What is mix of technology penetration in each subsector?
- How efficient are vehicles?

Travel Demand (T)

- How much transport is required in each subsector?
- How can demand for one mode be shifted to other modes or reduced altogether?

Population (P)

Scenario

Vehicle Technology (E)

Fuel Mix (C)

- What fuels are used?
- What is the fuel mix in each subsector?
- How “green” are they (i.e. how are they produced)?
MANY PATHS ⇒ 80in50:
“Actor-Based” Scenario Meets 80% Reduction Goal via reduced travel demand, efficiency, biofuels in heavy-duty vehicles, electricity + H2
Common themes: scenario results

- Meeting long term GHG reduction goals will be extremely challenging
- Portfolio approach attractive ("silver bullet" scenarios not as attractive or feasible)
- Combination of approaches needed
STEPS Runs through 2010 ...
What’s next?
Evolving STEPS Research Goals

• Single pathway analyses =>
• Robust comparison of fuel pathways =>
• Integrative scenarios for future vehicles and fuels
• Case studies that inform carbon and alternative fuel policies in CA and the US
NextSTEPS Goals and Scope

• NextSTEPS will 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.

• We will develop detailed regional studies for the U.S., China, and possibly Europe.
NextSTEPS will expand the STEPS approach to create richer scenarios, tools, and policy analyses to inform key policy and investment decisions.

NextSTEPS will integrate four key research areas:

1. Dynamics of change in the transport sector
2. Models to support scenarios and transition strategies
3. Scenarios and transition strategies to inform industry planning and government policy
4. Policy evaluations: Reducing GHG emissions and meeting other sustainability goals
Future Research Directions

Scenarios and Transitions

• Vision different scenarios and realistic transitions

Expand Scope of Lifecycle/Systems Analysis

• Assess wider range of sustainability issues, GHG, air pollution, water, land, materials use, energy system reliability/resilience in holistic framework

Seek Greater Understanding of the Consumer

• Consumer values/behavior; implications of new information tech

New Vistas

• Integrate ITS-Davis work on urban planning and VMT with supply side modeling to look at low VMT/low carbon futures.
• Apply STEPS approach to new regions (China)