Optimal Control Options for Plug-in Hybrid Vehicles

Context Sensitive Battery Management Strategies for Hybrid Automobiles

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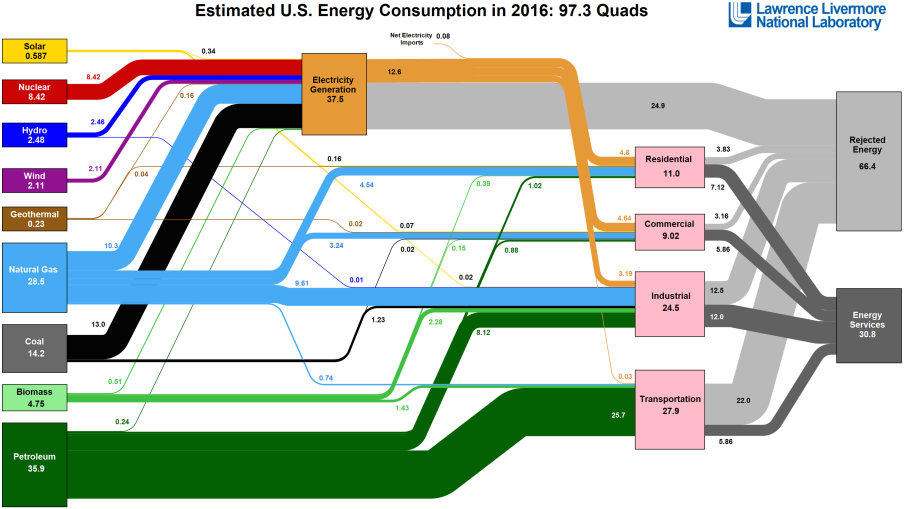
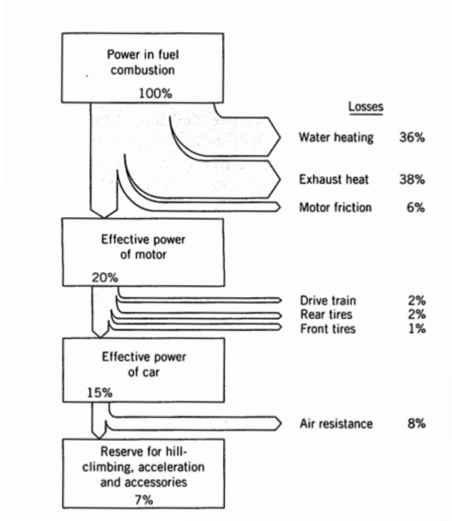
May 2 2017

US Energy Flow 2016 - efficiency, too



Estimated U.S. Energy Consumption in 2016: 97.3 Quads

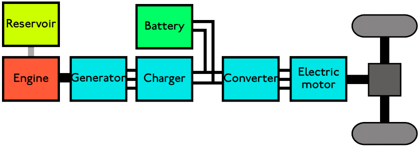
Efficiency of internal combustion engine



- Why is this so inefficient?
- How do Hybrid cars (e.g. a Prius) get higher efficiency? They still use internal combustion engines.
- How would electric drive vehicles compare?
- How do we make electricity for a vehicle fleet?
- Need a sort of "Wellhead to Wheel" efficiency to sort this out

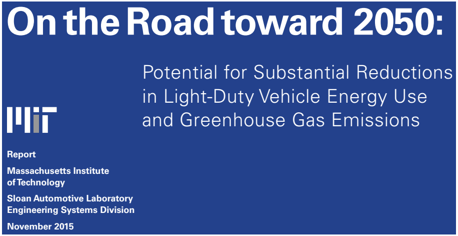
Plug-in Series Hybrid - Chevrolet Volt example

- Plug-In Hybrid uses both electrical and petroleum energy sources
- disadvantage - two drive trains, weight, complexity
- 35 -50 mile range as plug-in (9.3 gal tank, range 380 miles)
- fast refuel from fuel distribution, slow from grid



- Conventional modern IC engine
- Electric motor, regenerative braking
- Series Hybrid allows either, or, both drive approach
- 1.4L 84 HP (63 kW)
- 149 HP (111kW) electric motor
- 16 kWh battery capacity (435 lbs, 200kg)
- EPA 98MPG equiv 35/40 MPG
- (3781 lbs curb weight)

Estimates for PHEV Market Share



On the Road toward 2050:

Potential for Substantial Reductions
in Light-Duty Vehicle Energy Use
and Greenhouse Gas Emissions

Report

**Massachusetts Institute
of Technology**

**Sloan Automotive Laboratory
Engineering Systems Division**

November 2015

- Is there going to be an impact from PHEV vehicles?
- What fraction of the US fleet?
- MIT Sloan Study suggests PHEV market roughly equal to BEV market
- Practical advantages to electrical and petroleum fuel, unlimited range

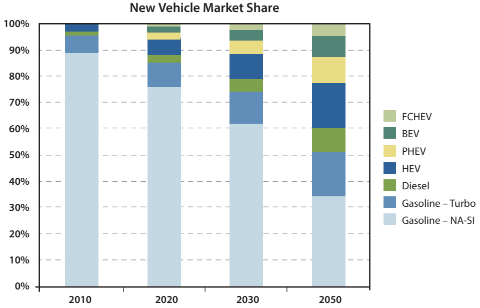
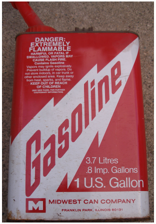


Figure 9.4 Powertrain market share input values 2010–2050.

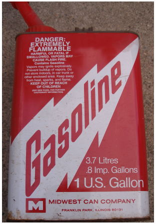
Context Sensitive Hybrid Battery Management

- Seed Grant, Precourt Institute for Energy Efficiency, Stanford
- Original proposal - two research tracks
  - Task 1 - Investigation of Route Estimator methods
  - Task 2 - Vehicle Resource management techniques, based on route knowledge
- Research directed at improving grid-sourced energy use in plug-in hybrids, minimizing fuel use

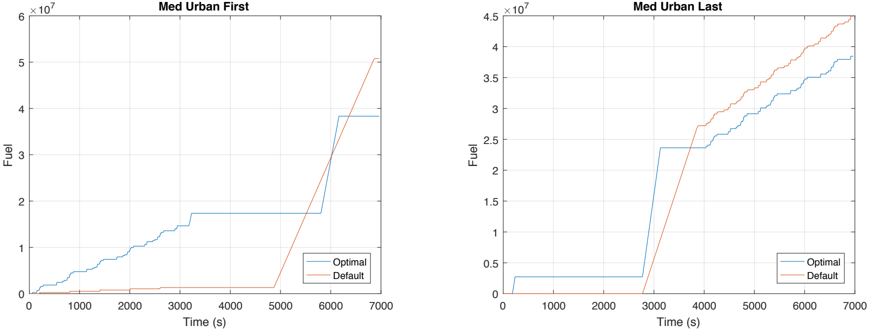


Context Sensitive Hybrid Battery Management

- Plug-In hybrid should maximally transfer energy from Grid, minimally use fuel resources
- Battery State-Of-Charge (SOC) - needs headroom to accept regenerative braking, downhill energy recovery
- SOC minimum to allow acceleration torque, electric efficiency
  - But when do you use each resource?
  - How do you decide to torque split gas vs. electric drive?
  - Do you ever recharge the battery from the petroleum?
  - Can you plan resources to end a trip with low SOC?
- Can you use knowledge of the trip energy profile (context) to optimally manage battery and fuel resources?



Optimal beats CDCS Conventional by 10% to 20%



- Compare Context-Sensitive Optimal Controller vs. Conventional (CDCS) controller fuel use
- Energy-equal routes, with energy profile differences
- Is this always true? How can we study this?

Research Directions

- Literature Review
    - Previous Work in route estimation from Nissan USA, Microsoft Research
    - Limited publications on optimal control using route information - recent Argonne paper, Larsson Chalmers University Ph.D. Thesis
- First decision - focus on optimal management with known route
    - Best match to graduate student interests
    - Defer Route Estimation for a later year, student with specific interest/expertise
- First efforts - investigate vehicle simulation tools and options to quantify energy on a determined route
    - Selection of Autonomie simulation tools for initial studies
    - Investigate battery technology for vehicles , understand series and parallel hybrid vehicle technologies
    - Investigate optimal control methods for hybrid engine vs battery tradeoffs, state of charge resource utilization

Autonomie Vehicle Simulator

- We build our simulation models, vehicle technology around the Autonomie matlab/simulink framework
- Developed at Argonne National Lab
- Allows quantitative studies of vehicle performance on specified route
- Outputs of primary system parameters
- Allows study of various controllers, studies of various vehicle technology choices
- Has significant amount of measured vehicle database, models of selected power plants
- Battery models including temperature effects

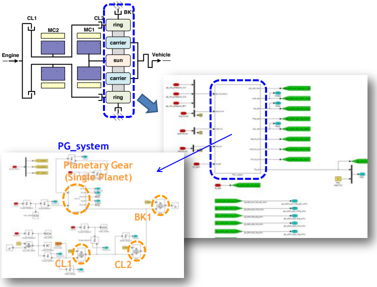


Figure 6 – Transmission model of the GM Voltec.

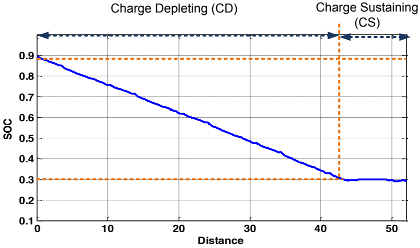
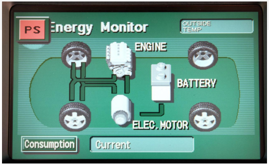


Figure 9 – Control strategy SOC behavior.

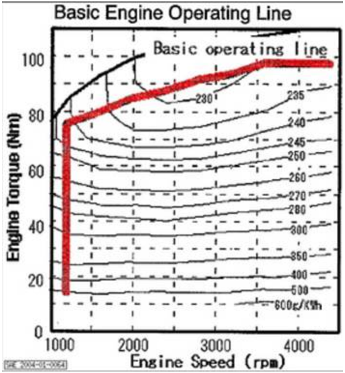
Parallel Plug-In Hybrid Vehicle Model

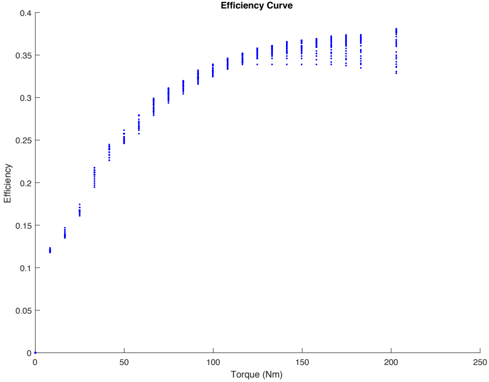


- Similar to Toyota Prius plug-in, but bigger battery capacity
- uses Automie hybrid controller models
- includes parasitic losses, battery losses, thermal models

- Autonomie IC engine maps (Honda Insight)
- Electric motors, regenerative braking
- Hybrid transmission (planetary gear) allows either, or, both drive approach
- Gas Engine 95 kW
- Electric motor 1 55 kW, motor 2 66 kW
- Battery capacity 7 kWh (4.4kWh Toyota)

Thottled Engines, Specific Fuel Efficiency vs Torque, Power and RPM



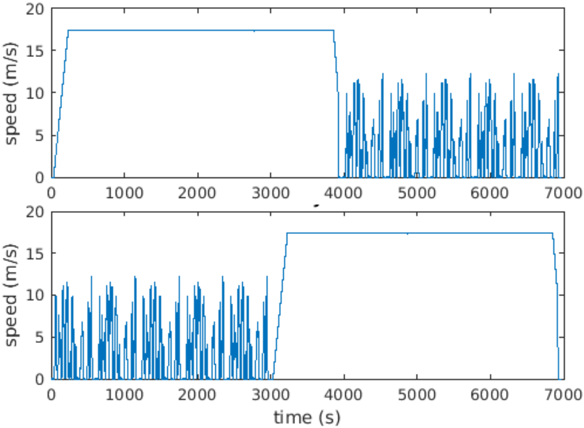


- Throttled engines - are most efficient at wide open throttle
- Efficiency vs. RPM a function of valve timing, induction effects
- But can you use all the power? Use Battery Resources to store fuel-derived energy
- Need Active Battery management -impacts from charge/discharge rates, heating, lifetime

compare two drive cycles, with equal-energy demand

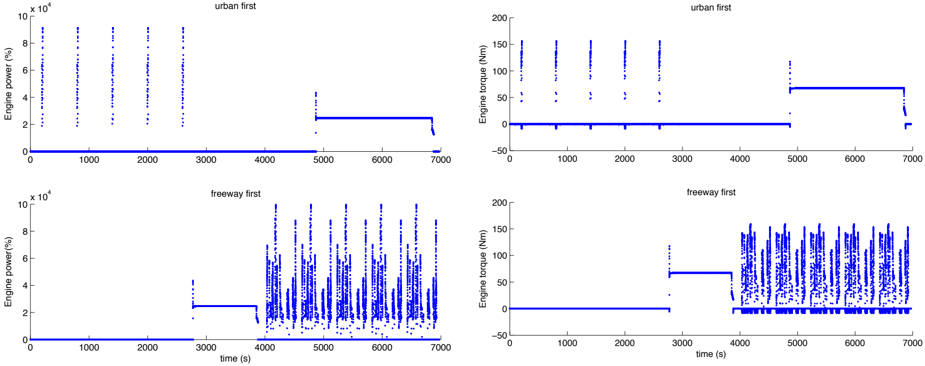
- We can evaluate various controllers, on two energy-equal routes
- This lets us quantify possible impacts of resource optimization
- Conventional Controller (CDCS)- use battery first, when SOC is 30%, become a hybrid

- Cruise First
- Urban Stop and Go First



CDCS Controller - Route Engine Power, Torques

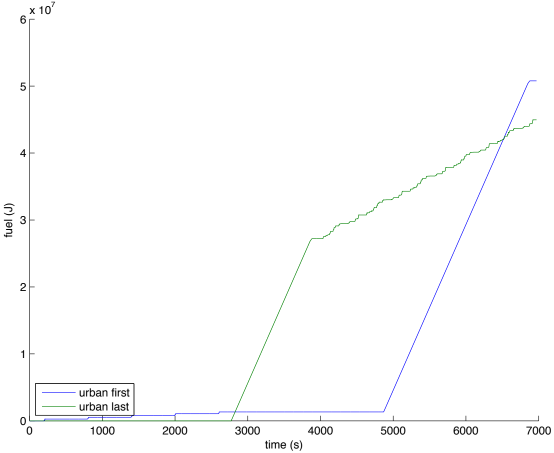
- Urban component - 5 NYC taxi cycles (lots of stop and go)
- Suburban (cruise) component - steady state cruise (no stop and go)
- Conventional CDCS Controller



- Very different torque and power profiles (Gas engine)
- Total Energy of the route is the same in both cases

Conventional CDCS Controller Fuel Use

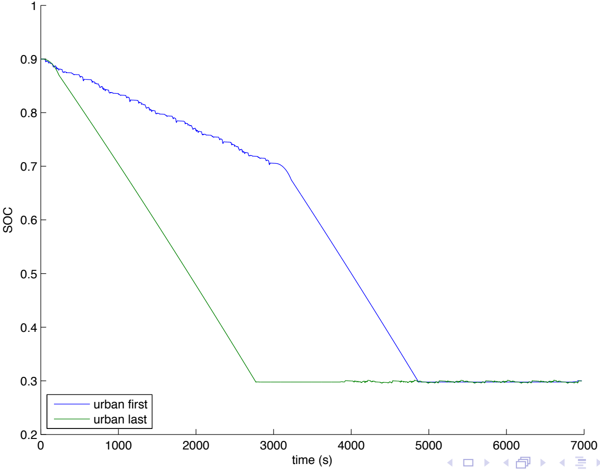
- Identical total energy demand both routes
- Any variation in consumption is strictly from resource management
- Can we do better than this? Fuel use 4.4 to 5.1 $\times 10^7$ J



- In this example, scheduling of battery use - roughly 10% difference

CDCS Controller - Battery usage two routes

- Identical energy both routes
- Battery State of Charge (SOC) reflects use during trip power, torque profile

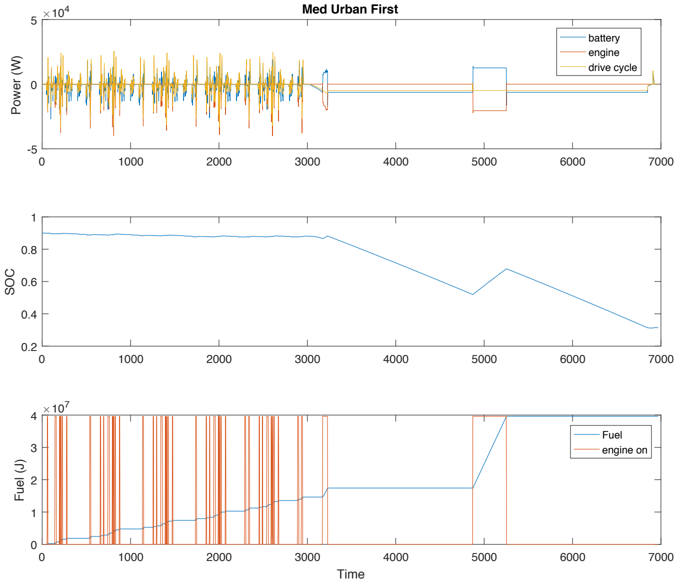


Optimal Control via Convex Optimization

- We find the minimum-fuel control by (integer) convex optimization
- Uses a vehicle/route model to predict and optimize energy usage
- Considers
  - Gas Engine Specific Fuel vs Power, Torque and RPM
  - Efficiency and constraints of electric motors and engine planetary gearset
  - Battery losses (resistive-capacitive model, losses from internal series resistance)
  - Engine thermal minimum on-time efficiency costs
- Solved on the fly (<1 sec.)
  - enabled by fast algorithms and modern high throughput processors
  - can incrementally resolve problem with new information
  - Uses Convex Optimzation tools from Stephen Boyd
- Many versions possible, *e.g.*:
  - Minimize combination of: fuel use, battery use, engine cycling, battery stress . . .
  - Assume known route, or probabilistic route (*i.e.*, true route is one of several candidates)
- Allows study of various controllers, studies of various vehicle technology choices (use as a tool to optimize vehicle characteristics). Optimal solution applied to Autonomie model vehicle via engine state parameters

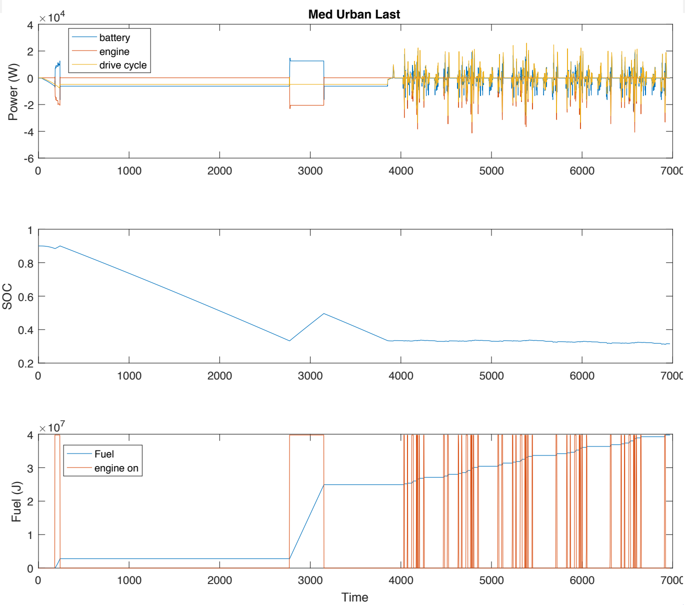
Optimal Controller fuel, battery SOC Urban First

- convex-optimized hybrid battery controller, mixed urban-suburban route
- Urban component - 5 NYC taxi cycles
- Suburban (cruise) component - medium speed steady state cruise
- Data is Urban First optimal

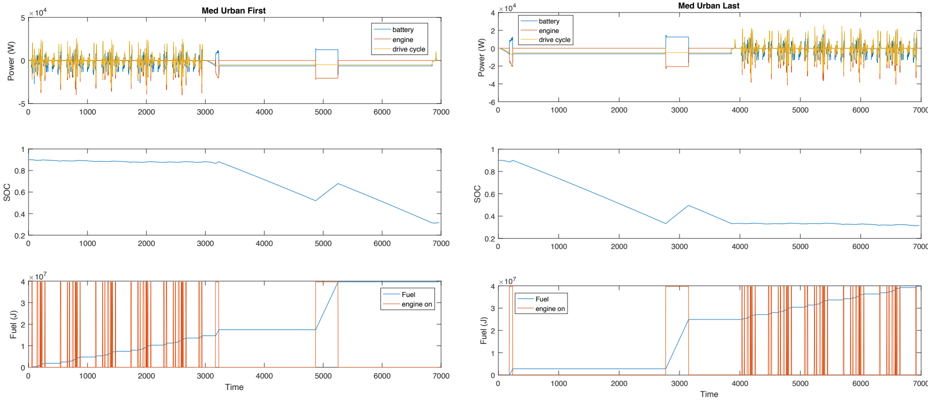


Optimal Controller fuel, battery SOC Urban Last

- convex-optimized hybrid battery controller, energy-equal routes
- Urban component - 5 NYC taxi cycles (lots of stop and go)
- Suburban (cruise) component - steady state cruise (no stop and go)
- Data is Urban Last optimal

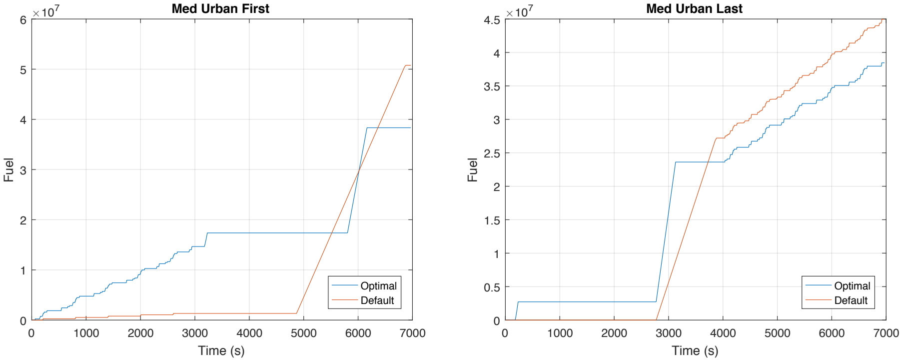


Optimal Controller comparison, urban first/last



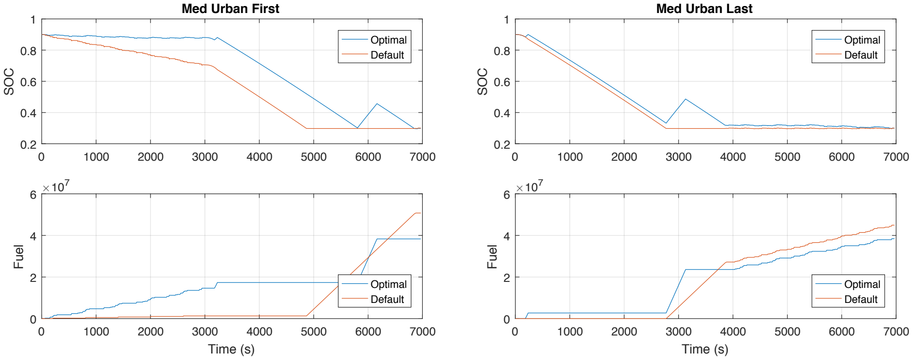
Can we compare histograms of engine power output, engine run time, etc. to better understand how the optimal solution is different from CDCS?

Fuel for two routes, optimal-control vs. CDCS



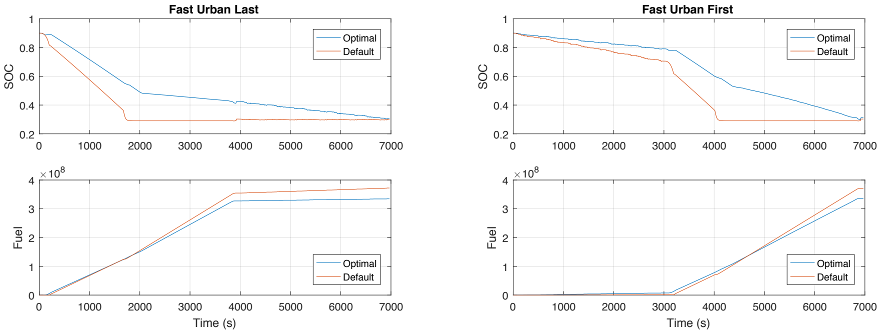
- convex-optimized hybrid battery controller, energy-equal routes
- Compare with same routes using Conventional (CSCD) controller
- in both cases - Optimal beats Conventional by $>$ 10% to 20%
- Optimal uses same fuel both routes

Fuel, Battery SOC for two routes, Optimal vs. CDCS



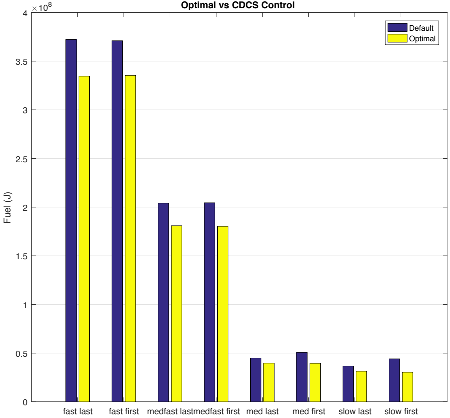
- Convex-optimized hybrid battery controller, energy-equal routes
- Compare with same routes using Conventional (CDCS) controller
- Both Optimal vs. Conventional Controller SOC end at 30%
- Both controllers run the engine, but at what torque and RPM?

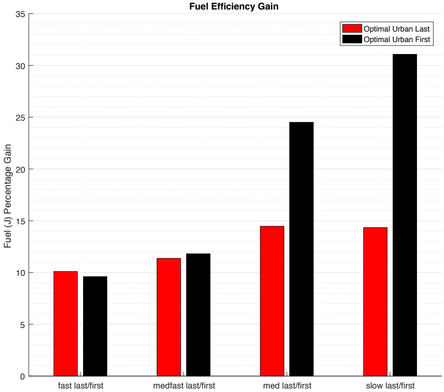
Fast Cruise, optimal-control vs. Conventional CDCS



- convex-optimized hybrid battery controller, energy-equal routes
- Compare with same routes using Conventional (CDCS) controller
- in both cases - Optimal beats Conventional by $>$10%
- higher cruise speeds pushes engine into higher efficiency range - less to optimize

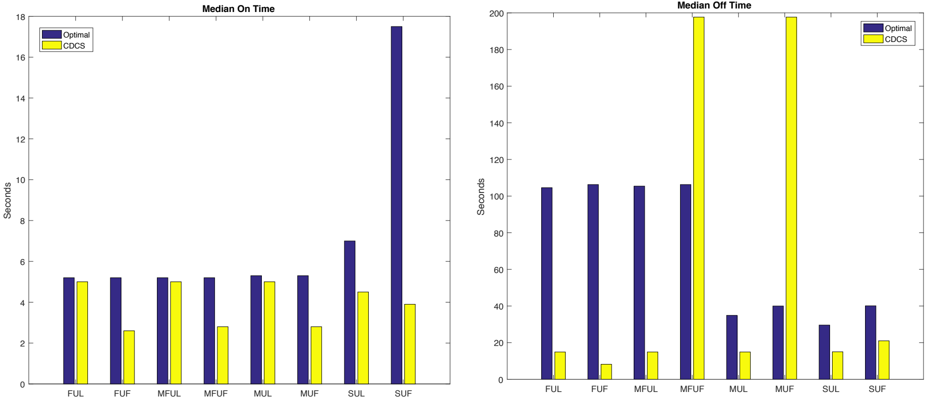
Fuel Comparison for 4 cruise speeds


Optimal vs CDCS Control


Fuel Efficiency Gain

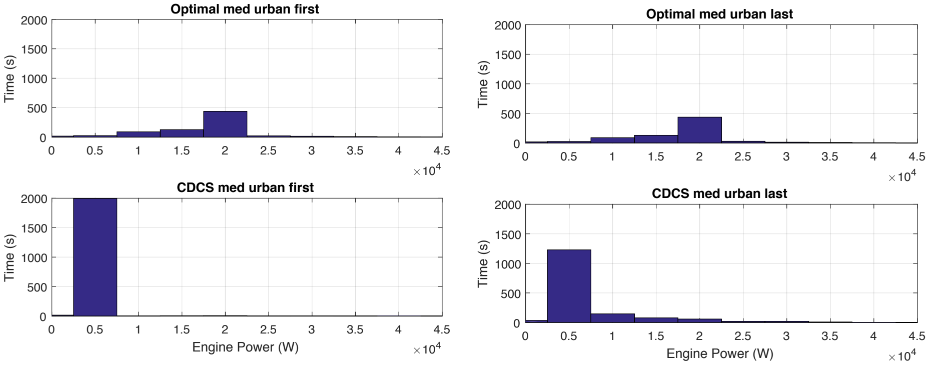
- convex-optimized hybrid battery controller vs. CDCS, energy-equal routes
- Compared for 4 cruise speeds (85, 65, 39, 28 mi/hr). Fixed 7000 sec cycle
- in all cases - Optimal beats Conventional by $>$10% to $>$20%
- higher cruise speeds pushes engine into higher efficiency range - less to optimize

Engine On/Off cycles, comparisons



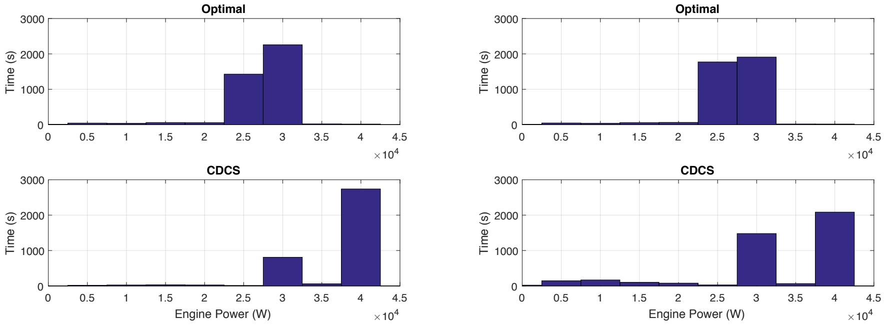
- convex-optimized hybrid battery controller vs. CDCS, energy-equal routes
- Compared for 4 cruise speeds (85, 65, 39, 28 mi/hr) Fixed 7000 sec cycle
- Possible Impact on economy from engine temp
- Optimal control cost on engine start

Engine Power Histogram Insight



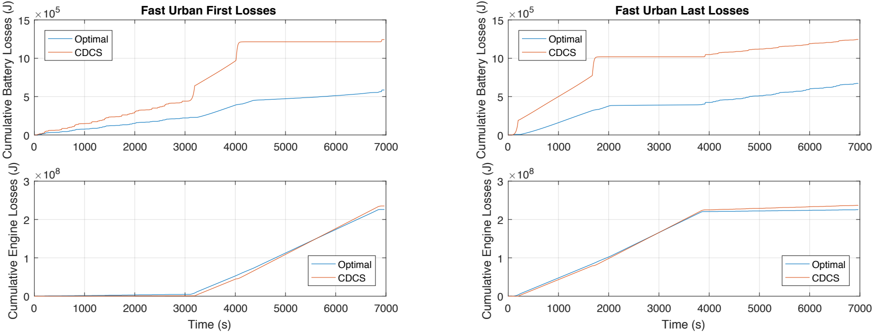
- convex-optimized hybrid battery controller vs. CDCS, energy-equal routes
- Medium cruise speed, fixed 7000 sec cycle, urban first (left) last (right)
- The optimal controller runs the engine at higher power, for shorter intervals
- higher power - higher specific efficiency (throttled engine)
- Is there an impact on the battery?

Engine Power Histogram Fast Routes



- convex-optimized hybrid battery controller vs. CDCS, energy-equal routes
- fast cruise speed, fixed 7000 sec cycle, urban first (left) last (right)
- The optimal controller runs the engine at lower average power
- Still achieves a fuel economy advantage
- This operating point minimizes combination of battery and fuel efficiency losses

Fast Engine Power Histogram, mystery explained

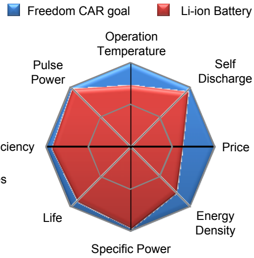


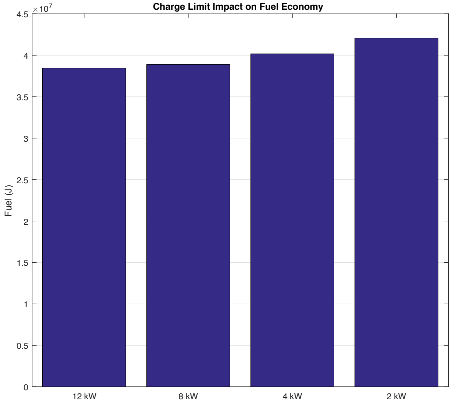
- This operating point minimizes combination of battery and fuel efficiency losses
- Battery losses - from internal resistance and charge/discharge currents
- Engine losses - efficiency of engine*fuel energy
- convex-optimized hybrid battery controller vs. CDCS, energy-equal routes
- fast cruise speed, fixed 7000 sec cycle, urban first (left) last (right)
- The optimal controller runs the engine at lower average power
- Still achieves a fuel economy advantage

Charge rates, Temperatures impact battery lifetime

"15-year life capable of delivering at least 55 kW for 18 seconds, 30kW continuous at a system cost of $12/kW."

"60% peak energy-efficient, achieves a 325W/kg and 220 W/L power density."





- To get good fuel efficiency, we run engine at high power output
- Battery is charged with extra engine power
- Study impact of limiting battery charge rate in optimal controller for medium route
- Compared for Autonomie (nominal), 2/3 , 1/3 and 1/6 nominal
- Thermal management of battery required at high charge rates, accessory power required
- Suggests balance of battery longevity and fuel economy possible

First Results - Conclusions

- The conventional CDCS Battery Controller is sensitive to route profiles
- Route variations for equal energy routes seen as 10% effect
  - Value of route knowledge
  - What sorts of optimal control methods work well?
- First Optimal Tests - convex optimization
- Fuel Economy increase over Conventional CDCS $>$ 10 to 15% for simple examples
- A promising first result
- Battery management might be part of an optimal solution
- Recent publications looking at statistical route information - ours is a complementary method

First Results - are promising

- The idea has value - demonstrated via simplified technology models and hybrid route study
- We have a technical framework to evaluate energy consumption of vehicles, and test controllers
    - Autonomie models - complex, can include battery technical limits
    - Reduced (simplified) controller - useful for Optimal control studies and technique evaluation
- We are just starting, now have an excellent framework for quantitive studies
- We can use this approach with actual trip routes, estimate savings in real-world trips
- We can study particular vehicles, or optimize vehicle properties to a route

Next Steps

- Concentrate on optimal methods, expansion of the convex optimization technique, computational feasibility
- Use database of actual routes, look at savings optimal vs. conventional, impact on real-world routes
    - distribution of energy profiles
    - potential efficiency increases on real-world routes and vehicle use patterns.
- Include battery technology models, and battery thermal and state of charge (SOC) limits in the route energy profile optimization. Economic (lifetime) optimization of battery management
- Investigate route estimation methods - the second central research direction
- Goals - Publications, submission of larger scale grant
- Collaborate with projects at ANL, new DOE-supported consortium
- Collaborate and expand contacts with Industry research
- Fully participate in Precourt, campus activity in Energy Efficiency

Our Interests

- Continue to explore optimal control of Plug-In hybrids
- Real-world routes and database of routes
- Explore Voltec (e.g. series) and Parallel Hybrid drivetrains, understand optimal control options
- Develop context sensitive vehicle designs (e.g. optimize the engine and battery capacities for various types of use patterns)
- We welcome collaborators with battery electrochemical expertise
- Partner with a vehicle manufacturer who would like to try these algorithms on a physical car

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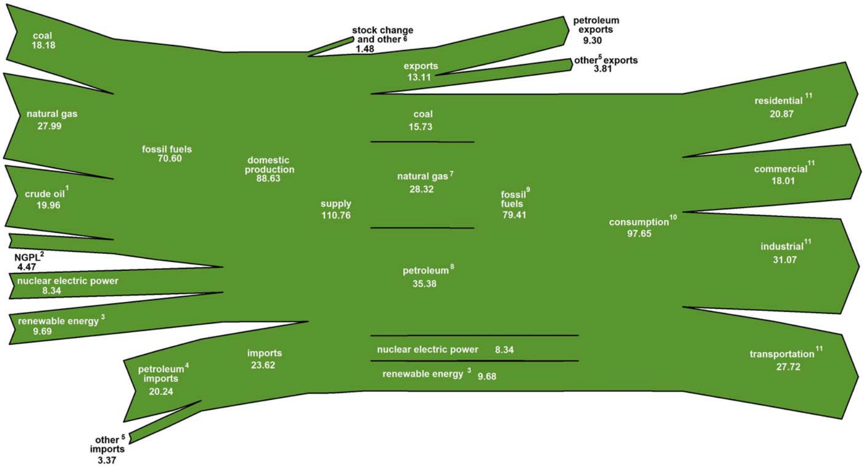
U.S. Energy Flow, 2015

quadrillion Btu



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[1] Includes lease condensate.
[2] Natural gas plant liquids.
[3] Conventional hydroelectric power, biomass, geothermal, solar, and wind.
[4] Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.
[5] Natural gas, coal, coal coke, biofuels, and electricity.
[6] Adjustments, losses, and unaccounted for.
[7] Natural gas only; excludes supplemental gaseous fuels.

[10] Includes 0.23 quadrillion Btu of electricity net imports.

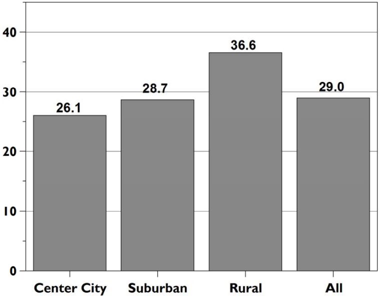
[11] Total energy consumption, which is the sum of primary energy consumption, electricity retail sales, and electrical system energy losses. Losses are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note 1, "Electrical System Energy Losses," at the end of U.S. Energy Information Administration, *Monthly Energy Review* (April 2016), Section 2.

Notes: • Data are preliminary. • Values are derived from source data prior to rounding for

What Plug-In electric Range is Useful?

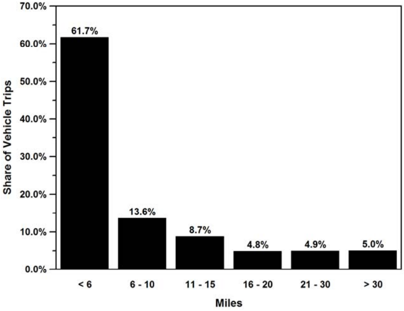
- Almost all trips are short - do you need 300 miles on a charge? What benefits come from a hybrid vehicle approach?

Figure 8.5. Average Daily Miles Driven (per Driver), 2009 NHTS



Source:
National Household Travel Survey, nhts.ornl.gov.

Figure 8.3. Share of Vehicle Trips by Trip Distance, 2009 NHTS



Possible Battery system models

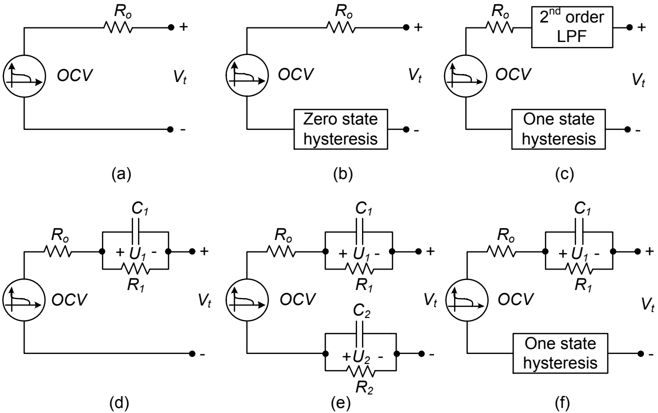


Figure 2.2 Six typical equivalent circuit models

we are using the simple type a) model in the optimal controller, Autonomie has other more complex battery models (type d)

Battery capacity vs. life cycles

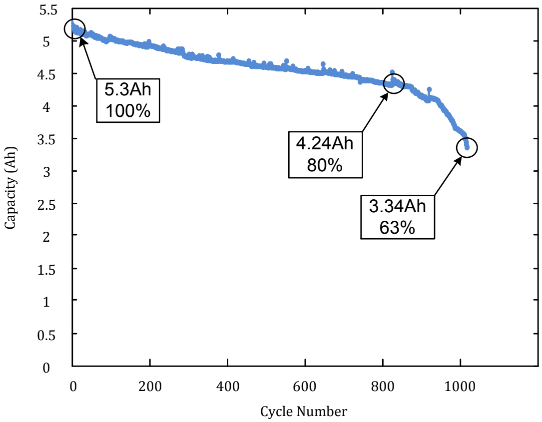
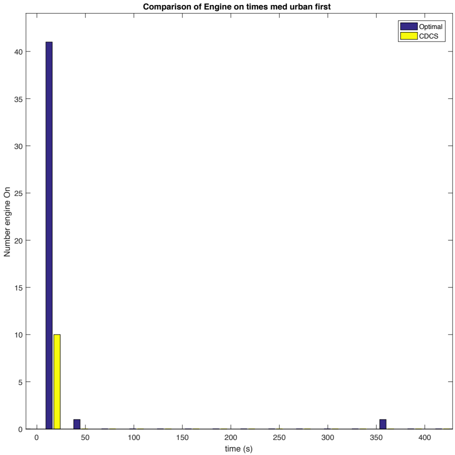
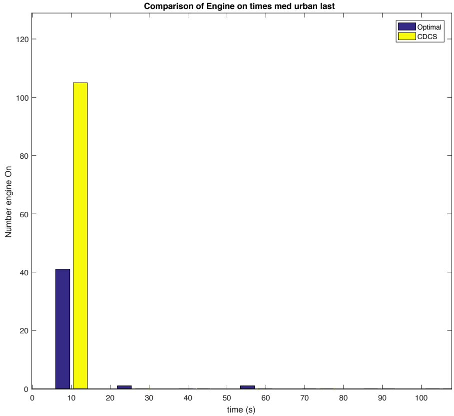


Figure 1.8 Li-ion battery capacity degradation as cycles increase

The rate of capacity loss is a strong function of depth of discharge and temperature of the battery during the charge cycle

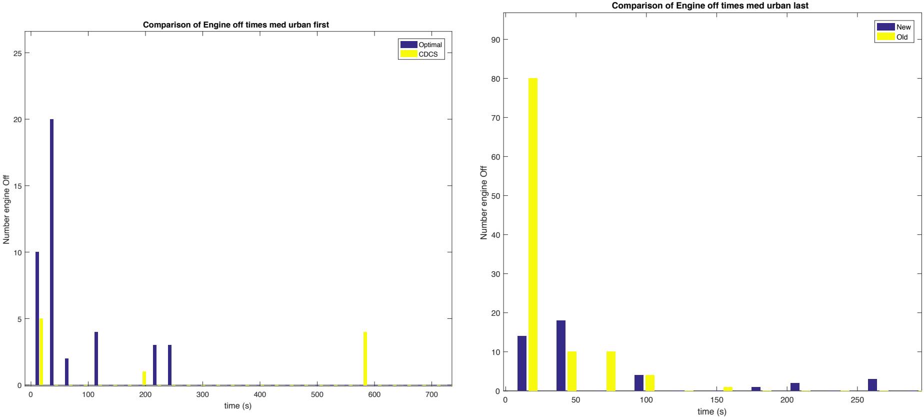
Engine On histograms


Comparison of Engine on times med urban first


Comparison of Engine on times med urban last

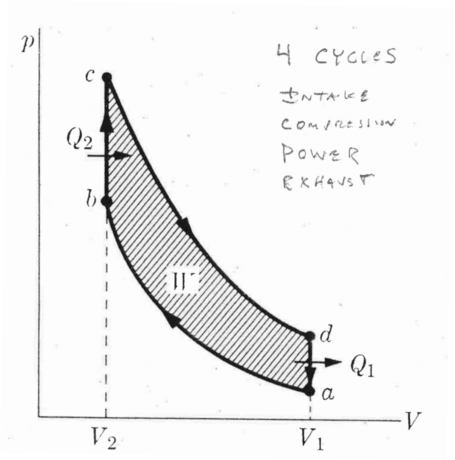
- convex-optimized hybrid battery controller vs. CDCS, energy-equal routes
- Engine ON time histogram
- Is tho short operating cycle realistic?
- Optimal control cost on engine start

Engine Off histograms



- convex-optimized hybrid battery controller vs. CDCS, energy-equal routes
- Engine OFF time histogram
- Possible Impact on economy from engine temp,cool down from long off
- Optimal control cost on engine start

Otto (Spark Ignition) Cycle



- Idealized cycle
- V_1 / V_2 Compression Ratio
- $\gamma = C_p / C_v$
- Efficiency $E = 1 - \frac{1}{\frac{V_1}{V_2}^{\gamma - 1}}$
- A throttled engine

More Real Otto (Spark Ignition) Cycle

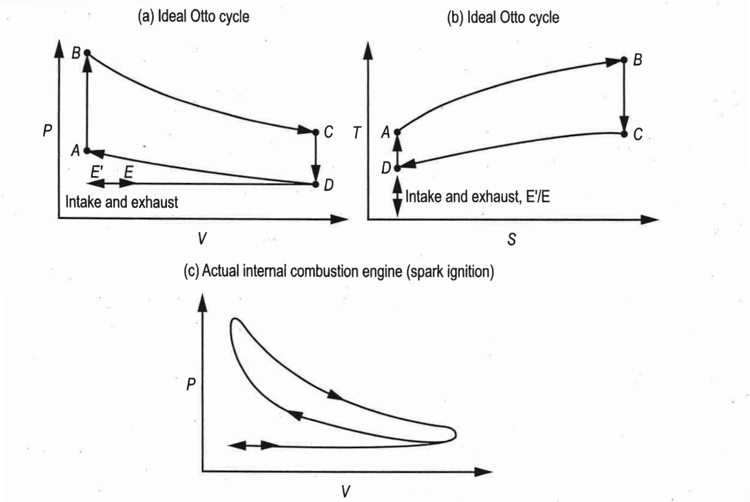
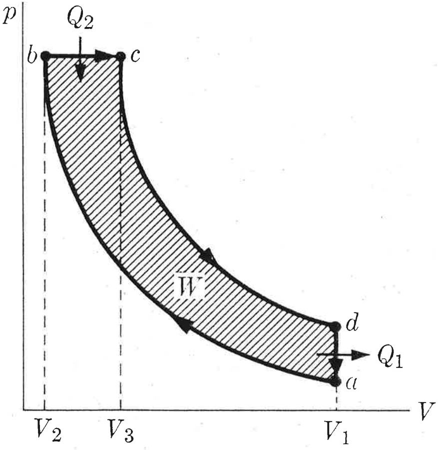


Figure 3.9. Power cycle diagrams for the spark ignition internal combustion (SI-IC) piston engine (i.e., the common automobile "gasoline" engine): (a) *P-V* and (b) *T-s* diagrams for the Otto cycle approximation, and (c) *P-V* diagram for an actual engine. Source: Tester and Modell (1997). Reprinted with permission of Pearson Education.

Diesel (Compression Ignition) Cycle



- Idealized cycle
- allows high V_1 / V_2 Compression Ratio (higher efficiency)
- What are Q_1 and Q_2 ?
- un- throttled engine (high efficiency)
- Issues with particulates in exhaust, NOx, noise
- increasingly popular in Europe, in US needs aftertreatment for emissions

More Real Diesel Cycle

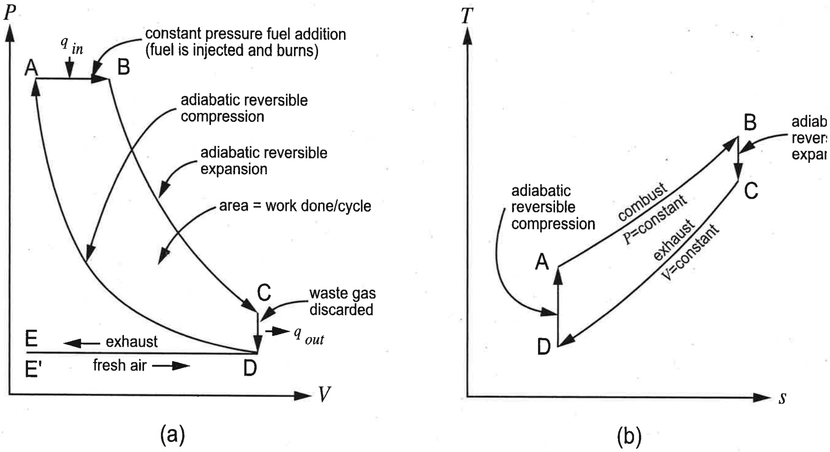
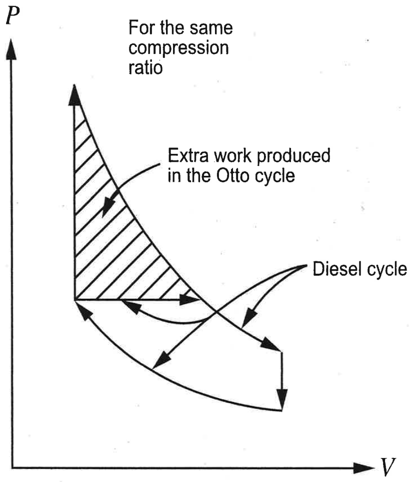
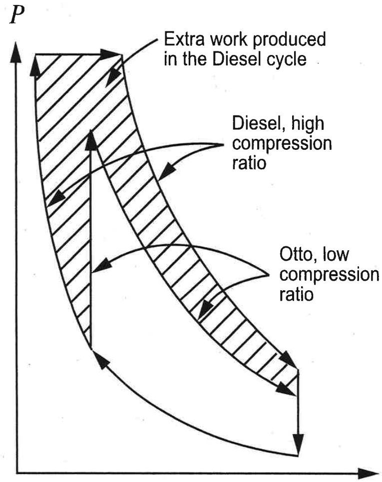


Figure 3.10. (a) *P-V* and (b) *T-s* diagrams for the diesel approximation of the compression ignition, internal combustion piston engine (i.e., the common automative diesel engine) power cycle. Source: Levenspiel (1996).

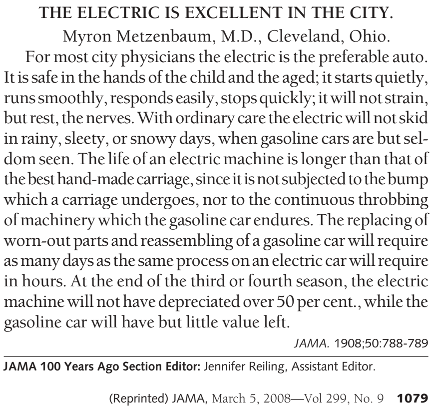
Efficiency Advantage Diesel vs Otto (throttled) cycles





Electric Cars - are the newest thing in transportation

- Letter to the Editor - Journal of the American Medical Association
- Dr. Metzenbaum (Cleveland Ohio) says the Electric Car is the best choice for the city doctor



THE ELECTRIC IS EXCELLENT IN THE CITY.

Myron Metzenbaum, M.D., Cleveland, Ohio.

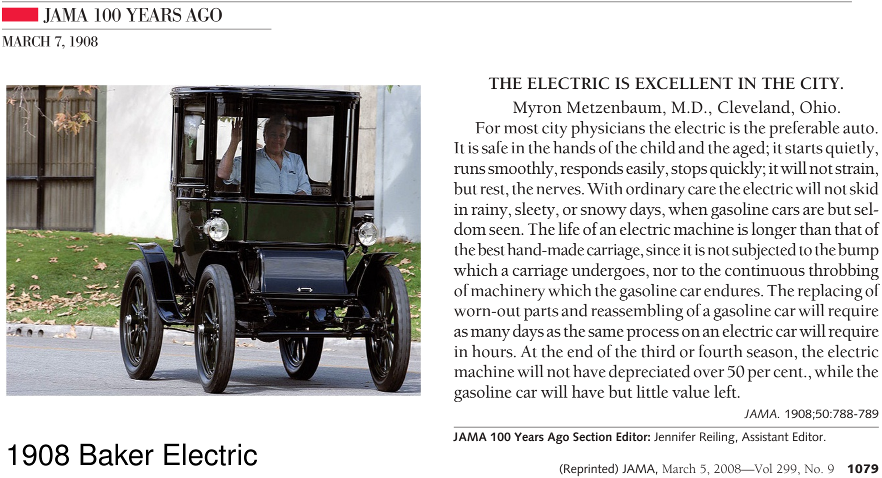
For most city physicians the electric is the preferable auto. It is safe in the hands of the child and the aged; it starts quietly, runs smoothly, responds easily, stops quickly; it will not strain, but rest, the nerves. With ordinary care the electric will not skid in rainy, sleety, or snowy days, when gasoline cars are but seldom seen. The life of an electric machine is longer than that of the best hand-made carriage, since it is not subjected to the bump which a carriage undergoes, nor to the continuous throbbing of machinery which the gasoline car endures. The replacing of worn-out parts and reassembling of a gasoline car will require as many days as the same process on an electric car will require in hours. At the end of the third or fourth season, the electric machine will not have depreciated over 50 per cent., while the gasoline car will have but little value left.

JAMA. 1908;50:788-789

JAMA 100 Years Ago Section Editor: Jennifer Reiling, Assistant Editor.

(Reprinted) JAMA, March 5, 2008—Vol 299, No. 9 **1079**

Electric Cars - are the newest thing in 1908



JAMA 100 YEARS AGO

MARCH 7, 1908

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1908 Baker Electric

Interesting Directions in 2015

- New concepts of car ownership
- Is the car still a personal statement?
- What about social media (crowdsourced) rides?

- Investments in urban plans, streetscapes
- Alternatives to decentralized living and working
- Last Mile investments
- Where do people want to live and work?
- check out www.walkscore.com

Fewer Youths Jump Behind the Wheel at 16

Erik S. Lesser for The New York Times

Kelsey Sheffer, 16, of Bethlehem, Ga., says she lost the motivation to pursue a full license after she saw accident sites with a police officer. For now, her mother is happy to shuttle her around.

By MARY M. CHAPMAN and MICHELINE MAYNARD

- Today's teens - less than 60% even have driver's licenses
- They would rather text than drive
- (I prefer not text AND drive)
- Future demand for personal vehicles?