Laboratory for Aviation and the Environment
Massachusetts Institute of Technology

Potential Environmental and Economic Benefits of Higher-Octane Gasoline

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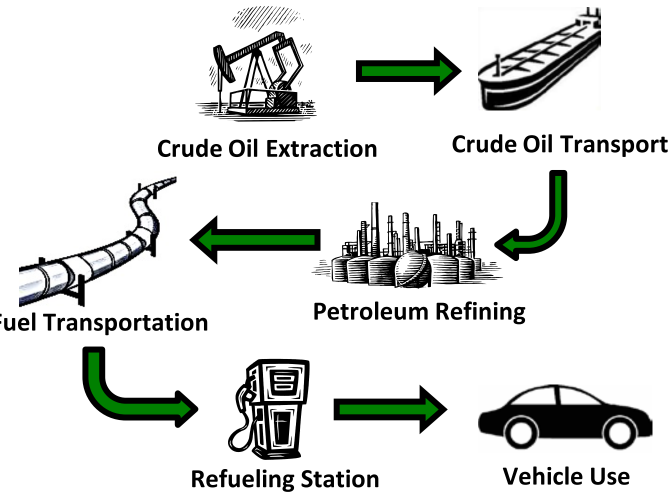
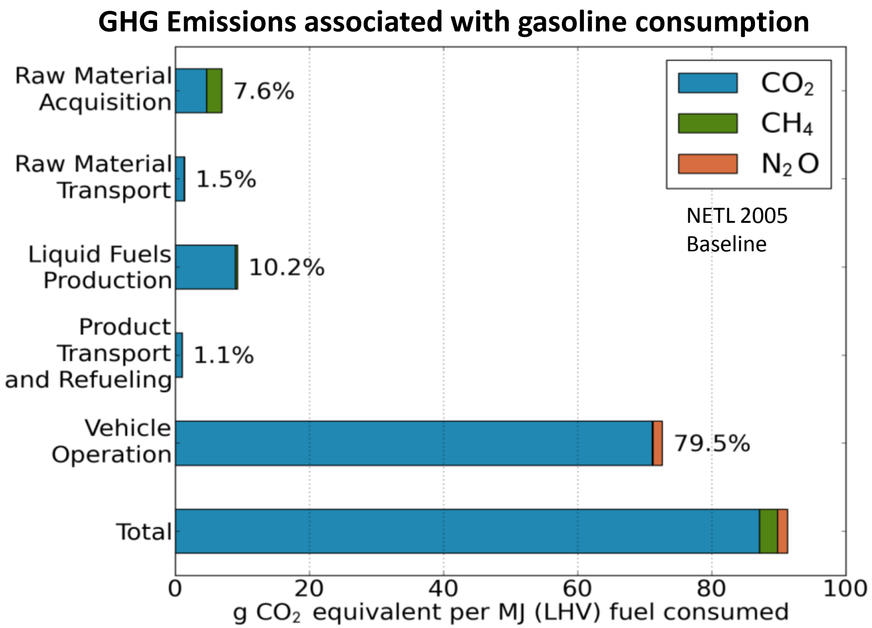
Background

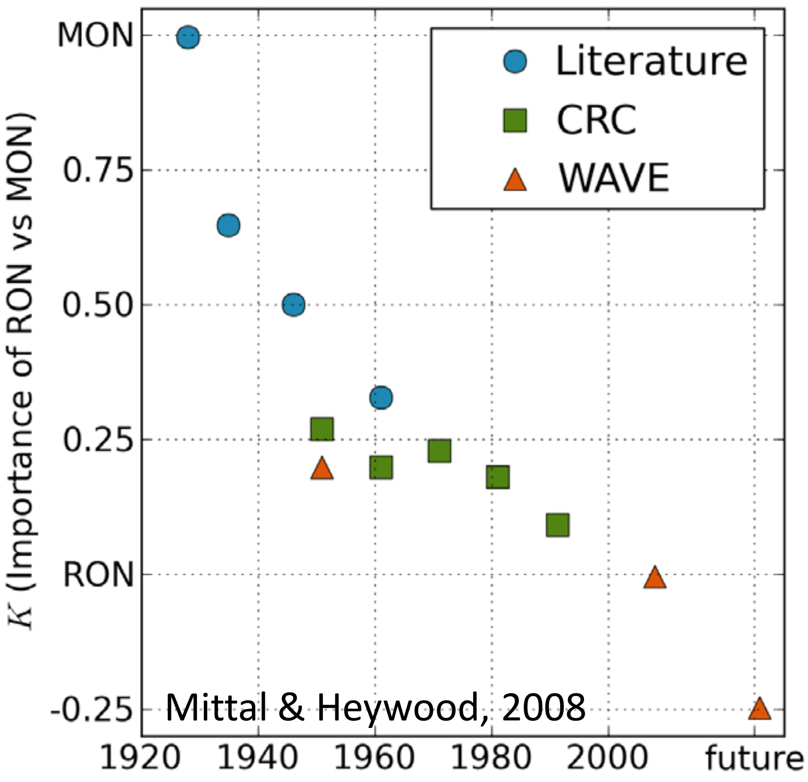
- Light-duty vehicles generate 17% of U.S. greenhouse gas emissions
  - 991 x 10^9 kg CO_2 in 2014
- Efficiency of spark-ignition engines is limited by knock
  - Higher-octane fuels are more resistant to knock
  - Refining high-octane fuels requires more energy and produces more GHG emissions
- Majority of lifecycle CO_2 emissions occur during vehicle operations
- Would increasing the octane rating of gasoline result in a net emissions decrease?





Knock & Octane Ratings

- Occurrence of knock depends on a combination of fuel properties, engine design, and operating conditions
- Knock resistance of fuels characterized using two tests:
  - Research Octane Number (RON): 600 rpm, *inlet air* heated to 50° C
  - Motor Octane Number (MON): 900 rpm, *fuel/ air mixture* heated to 150° C
  - RON test includes effects of fuel vaporization; MON test does not
- Changes in engine design have shifted relevance of the tests



Potential of Higher-octane Gasoline

- Higher-octane fuels will allow for more efficient vehicles
  - How much more efficient?
- Refining high-octane fuels requires more energy and produces more GHG emissions
  - How much more energy?
  - Ethanol blending reduces demand for high-octane petroleum blendstock, leaving refineries with spare capacity
  - Increasing fuel economy leads to lower gasoline consumption and spare capacity
  - Targeting RON only would increase refinery flexibility
- Interested in finding the octane standard that maximizes societal benefit (combination of reduced costs and reduced GHG emissions)

Effect of Octane Rating on Efficiency

- RON vs. compression ratio (r_c):
  - Increasing r_c by 1 requires 4–6 RON increase[1]
- Compression ratio vs. efficiency:
  - Increasing r_c by 1 gives a relative engine efficiency gain of 2.4% for naturally aspirated engines[2] and 3.9% for turbocharged engines
- Increasing r_c allows engine downsizing, which increases fuel economy further
- Fuel economy increase for a 6 point increase in RON:
  - 3.0–4.5% for naturally aspirated vehicles
  - 4.9–7.1% for turbocharged vehicles

1: Russ, 1996; Okamoto, 2003; Kalghatgi, 2005; Duleep 2012
2: Nakata, 2007; Munoz, 2005; Chow 2014

Proposed Scenario

- Replace current octane specifications with 92 RON regular, 98 RON premium
- Adoption timeline:

2015
- Current day

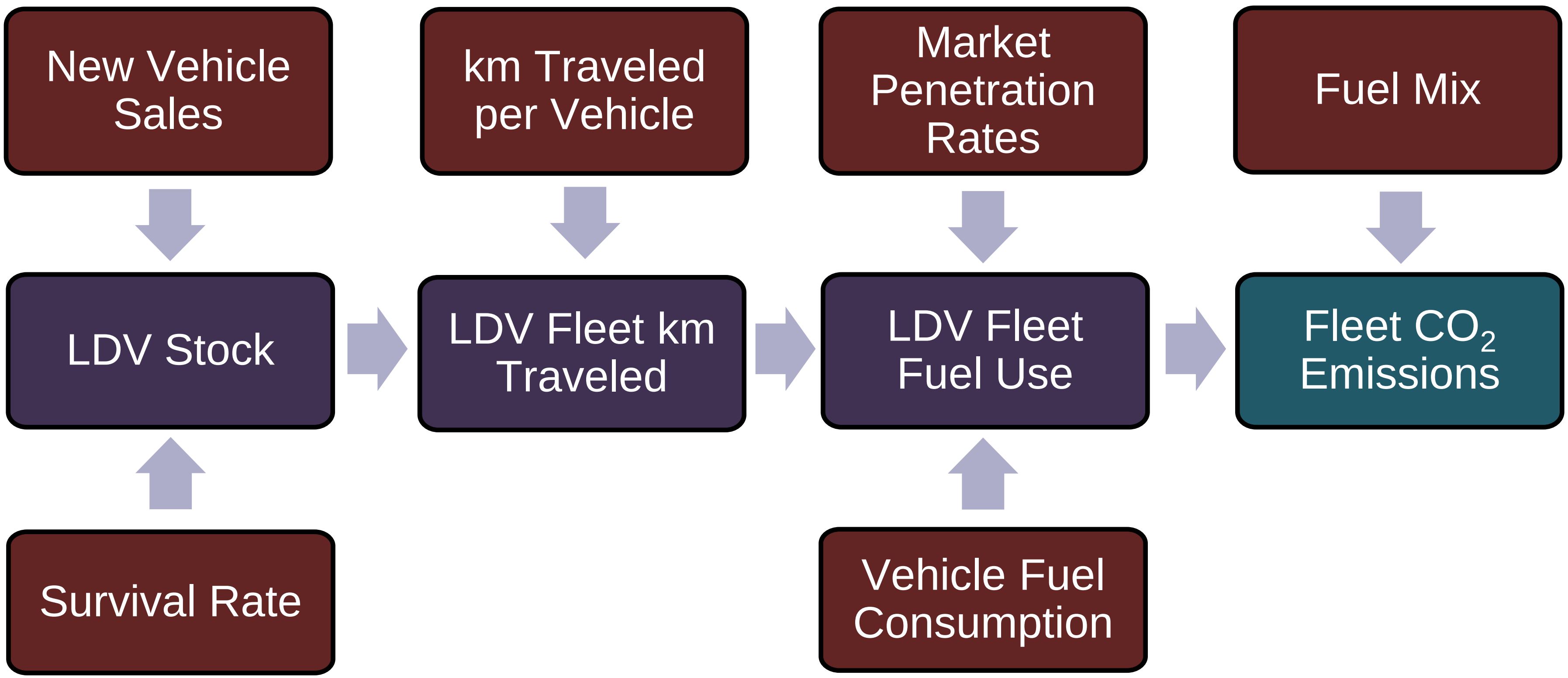
2020
- Manufacturers start introducing engines designed for higher-octane gasoline

2030
- 100% of the vehicle sales are of the higher-octane version

2040
- Examine fleet at a point where most on-road vehicles utilize high-octane gasoline

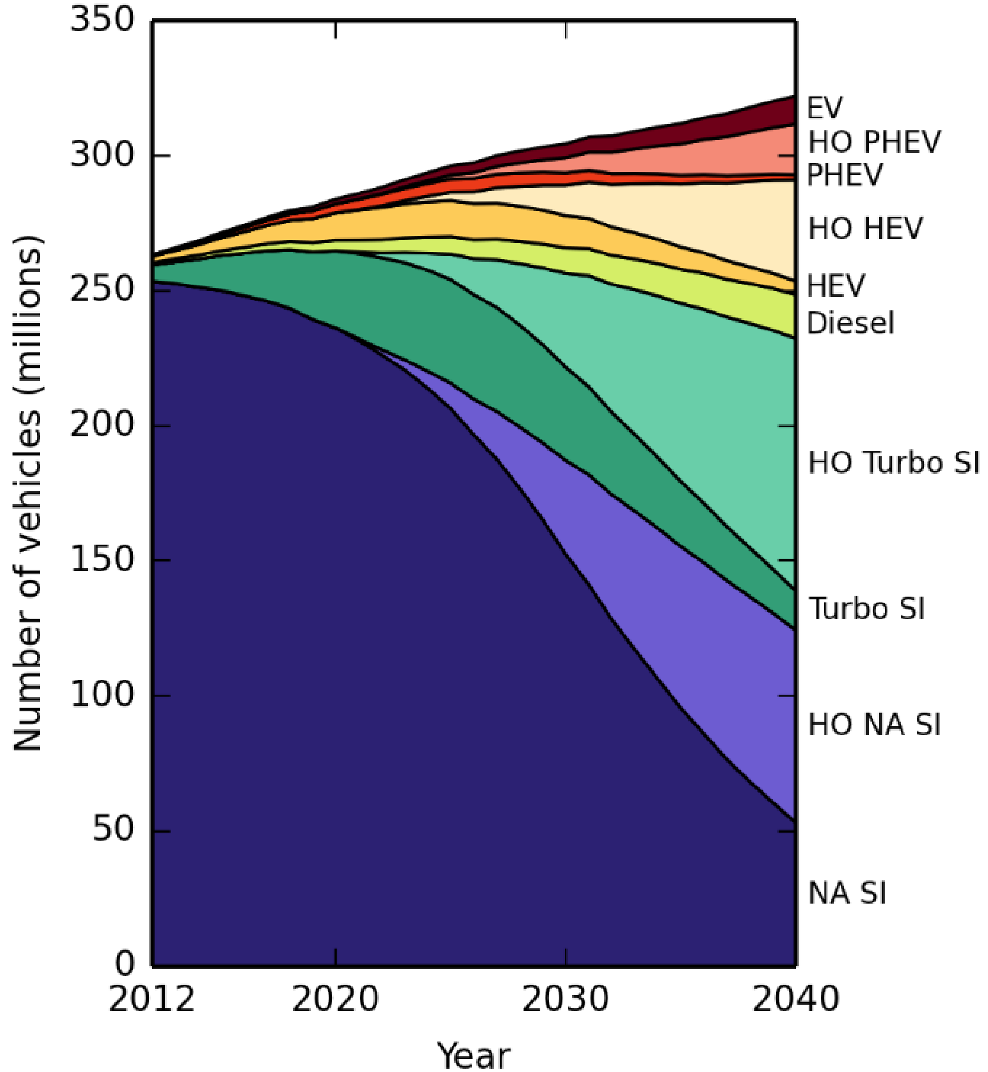
Fleet Model

- Describes the evolving characteristics of the future vehicle fleet: composition, size, vehicle kilometers traveled, fuel economy



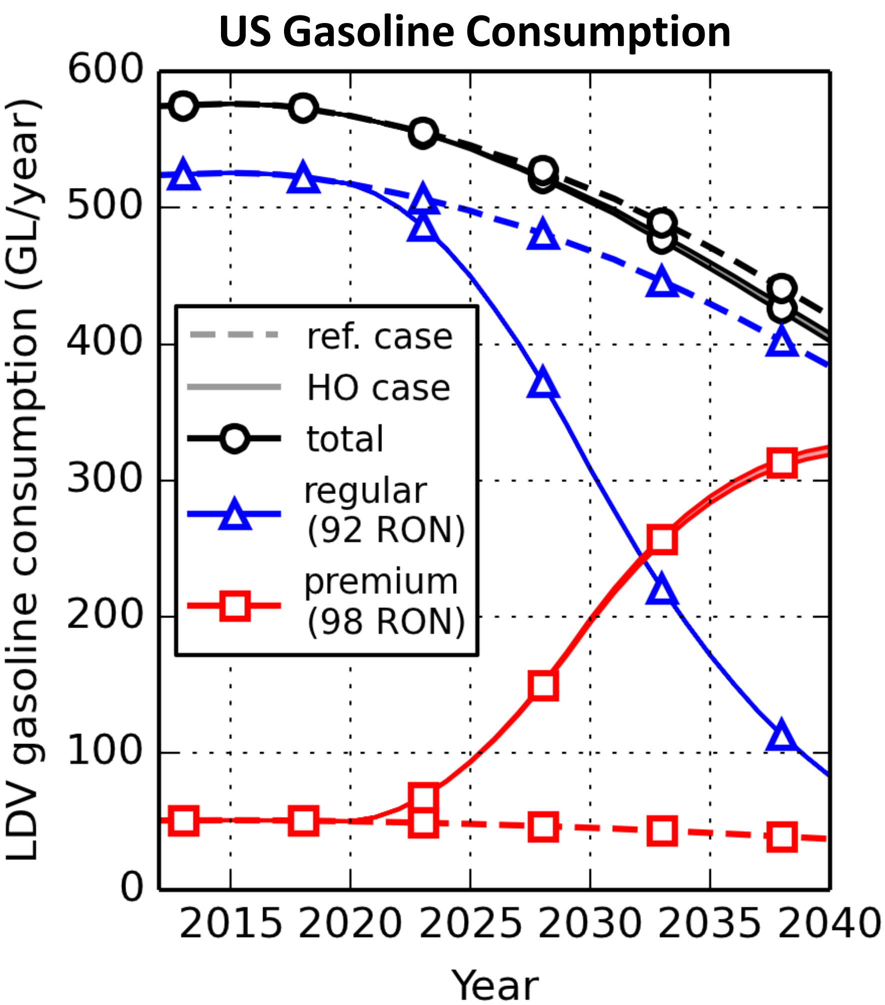
Light-duty Vehicle Fleet Model

- High-octane (HO) vehicles in each class gradually displace standard engines
- HO vehicles become majority in 2034
- 75% in-use vehicles use high-RON fuel in 2040



Evolution of Gasoline Consumption

- Gasoline consumption based on vehicle and fleet modeling
- Current market is approximately 10% premium
- Baseline: overall consumption reduced by 27% in 2040
- With higher-RON gasoline, consumption in 2040 decreases by 3.0–4.4%
- Growth in HO vehicles requires shifting production to 80% high octane in 2040



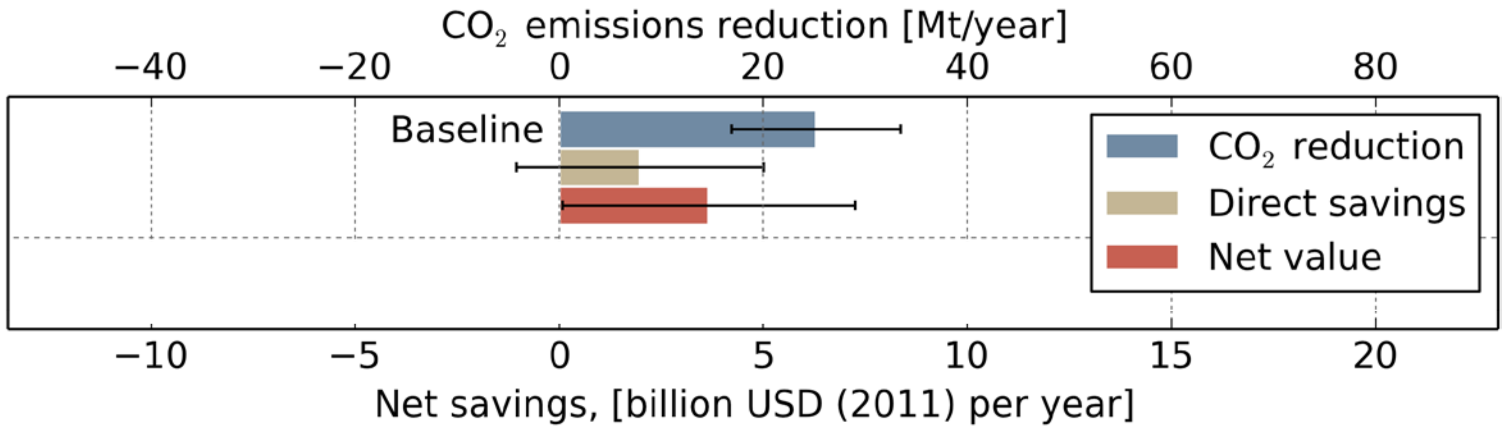
Refinery Model

- Linear programming (LP) approach
  - Linearized process model with process and product property constraints
  - Determine refinery product slate to maximize profit
  - Solved using Aspen PIMS (Process Industry Modeling System)
- Using modified Aspen "Gulf Coast" refinery model
  - Fixed crude slate, capacity set to 100,000 barrels / day
  - Added 10% ethanol blending for all gasoline grades
  - Prices set using EIA estimates for 2040
  - Additional modifications considered in sensitivity analysis
- Compute results for 2040, comparing two cases:
  - Reference case: 90% regular, 10% premium
  - "high octane": 20% regular, 80% premium

Environmental Analysis

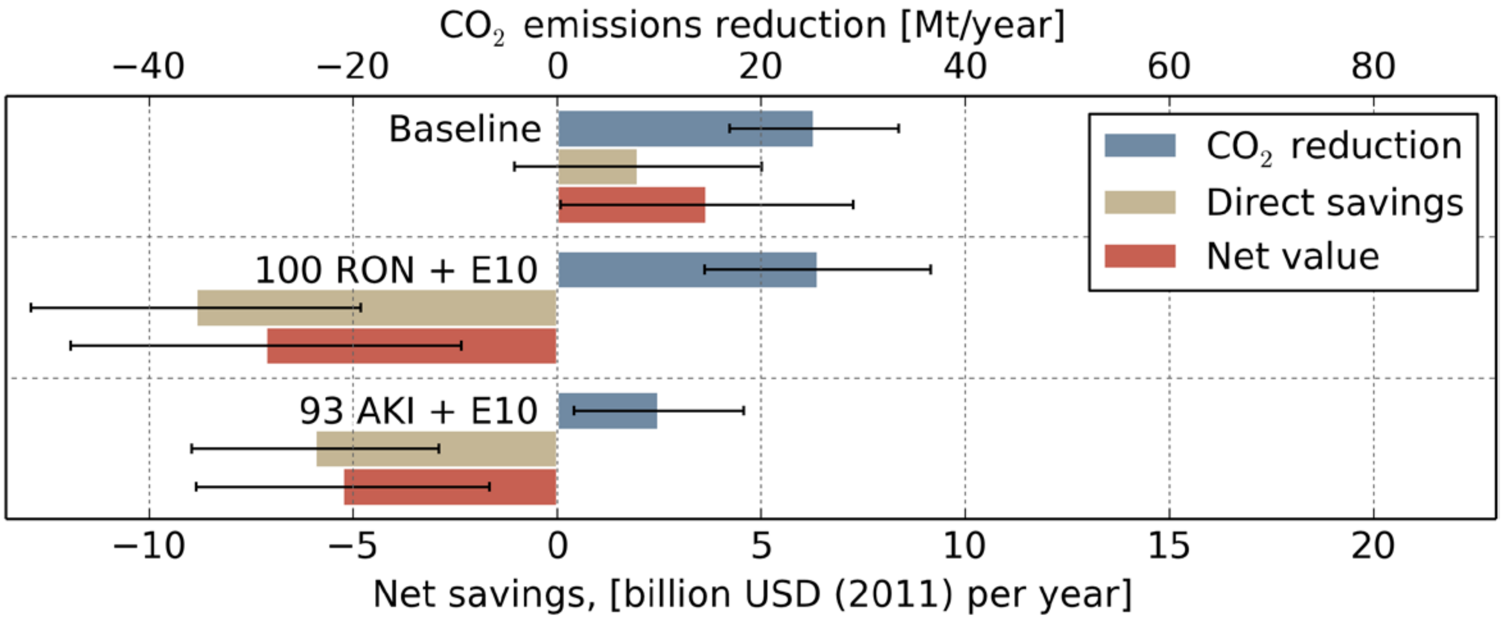
- Well-to-wheels CO_2 emissions
  - Consider a system consisting of the refinery and the consumers of all the refinery's products
  - Changes in the refinery product slate are balanced by displacing imports or exports of other fuels
  - Include the upstream emissions associated with these fuels
- Use social cost of carbon to monetize CO_2 emissions
  - Current estimate for emissions in 2040: $66 per ton
    - Equivalent to $0.59 per gallon of gasoline
- Evaluate total impact for the U.S.
  - Attribute all changes in emissions and costs to the octane change
  - Scale single-refinery results to match U.S. gasoline consumption
    - 2040 baseline consumption: 7.2 million barrels per day

Baseline Scenario Results



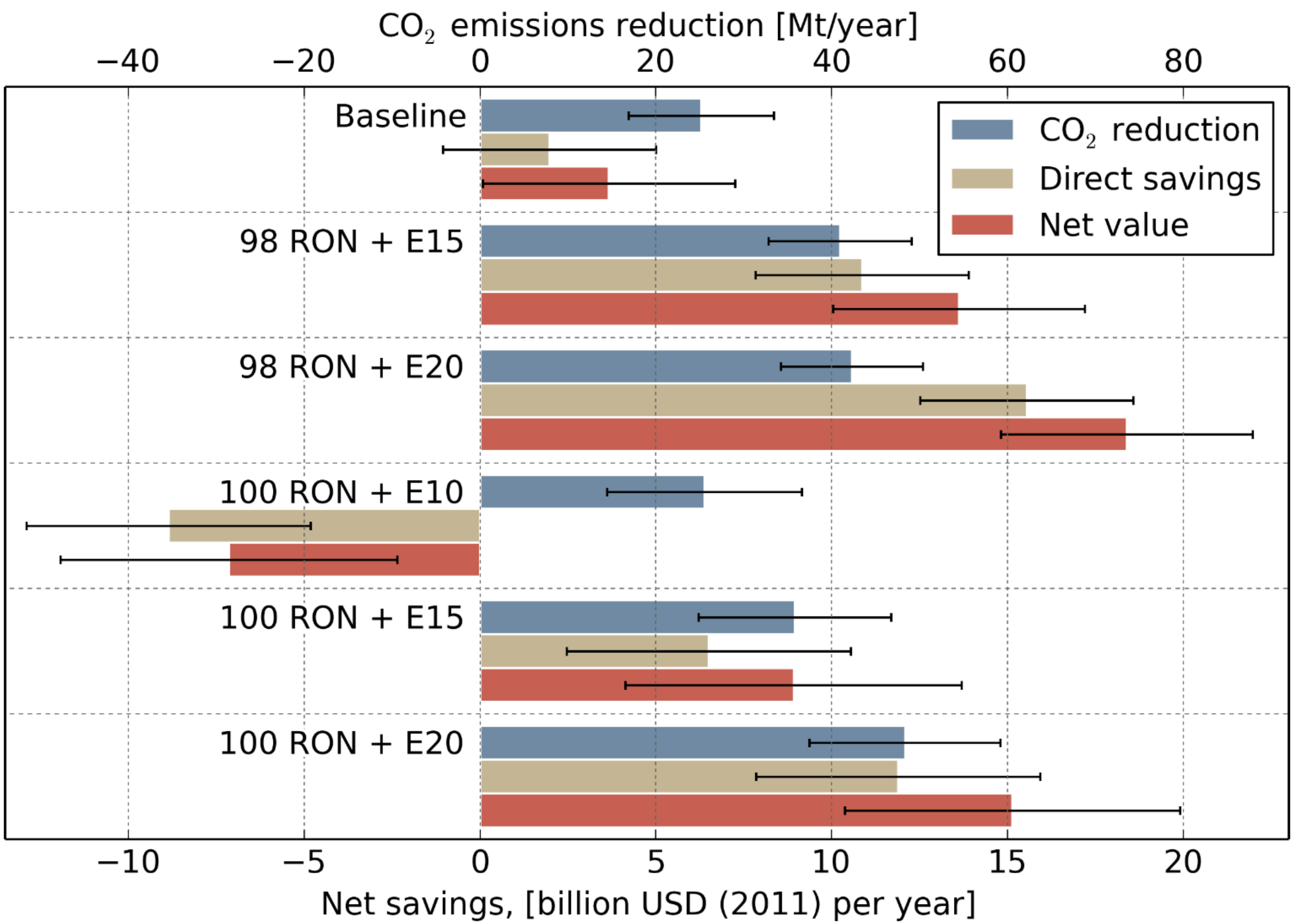
- Reduction in CO_2 emissions: 17 – 33 million tons / year
- Social cost of carbon: $1.2 – 2.2 billion saved
- Direct annual economic impact: between $1.1 billion cost and $5.1 billion savings
- Total value: $0.1 – 7.3 billion savings (Up to $37 per driver, per year)

Sensitivity: Octane Specification



- Increasing RON of premium results in a net societal loss
- Keeping current octane standards (AKI) results in a net societal loss, and lower CO_2 emissions reduction

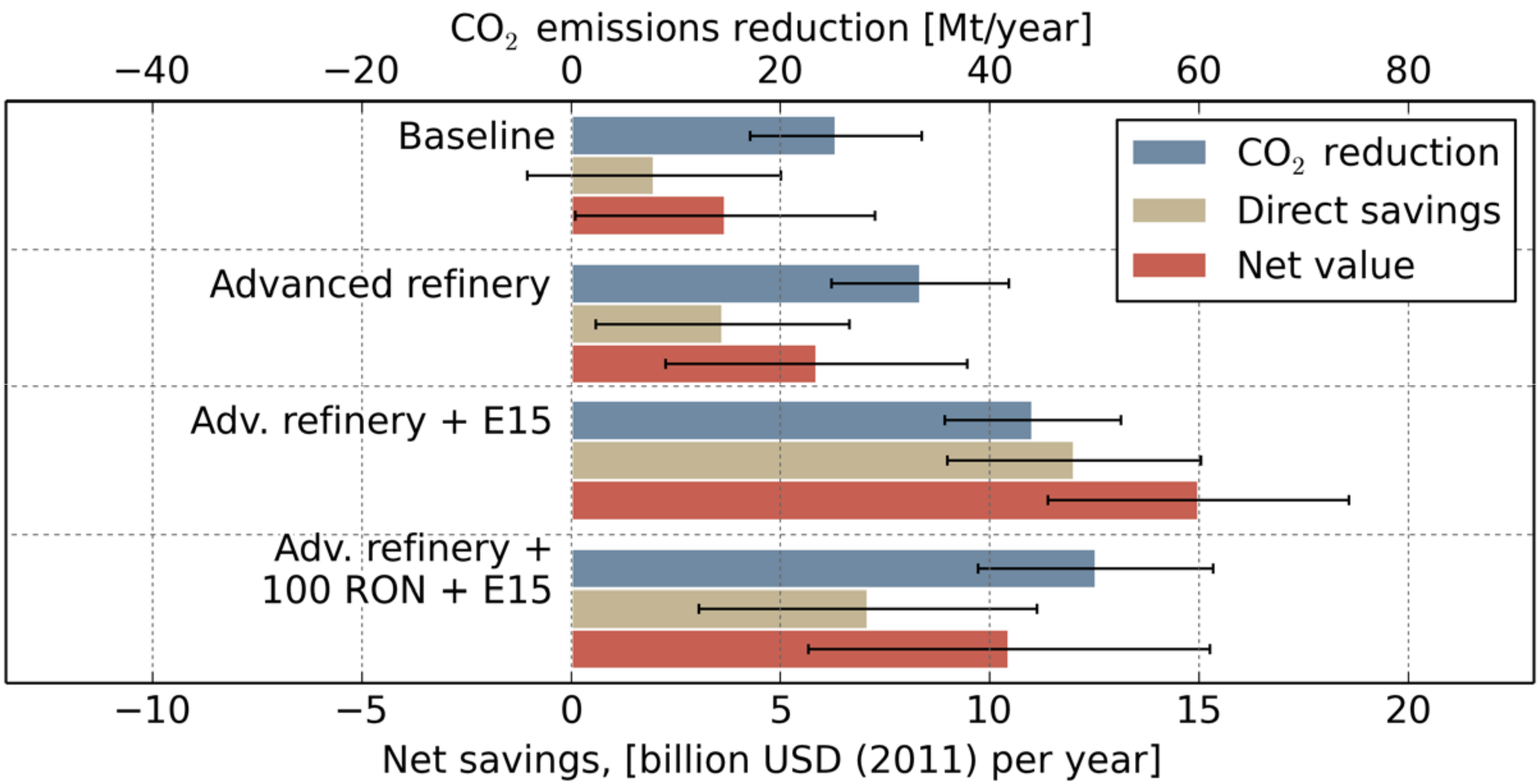
Sensitivity: Ethanol Content & Octane Rating



Advanced Refinery / Increased Capacity

- Refinery upgrades to allow production of additional high-RON gasoline:
  - Relax capacity constraints:
    - Coker
    - Alkylation unit
    - Hydrocracker
  - Additional process units
    - Propylene dimerization
- Higher GHG emissions associated with additional processing

Advanced Refinery Sensitivities



Summary

- Higher-octane gasoline can give a modest boost to vehicle fuel economy
- Refineries should be able to produce more high-octane gasoline without significantly increasing GHG emissions
  - Increasing ethanol blending to 15% would reduce changes to refinery operations and provide additional CO_2 reduction
  - Small refinery capacity expansions could make up for reduction in gasoline production
- Realizing a significant economic benefit from high-octane gasoline requires switching from AKI to RON

Questions for Future Work

- How would the costs and benefits be distributed?
  - Consumers (better fuel economy, but extra cost of premium currently exceeds fuel economy benefit)
  - Refiners (high-octane fuel costs more to produce, but price of premium reflects other factors)
  - Car manufacturers (high-octane fuel makes CAFE easier to meet, but vehicles may be more expensive to manufacture)
- What is the actual relationship between RON and fuel economy?
- How will differently-configured refineries behave?
- How would non-CO_2 emissions change?

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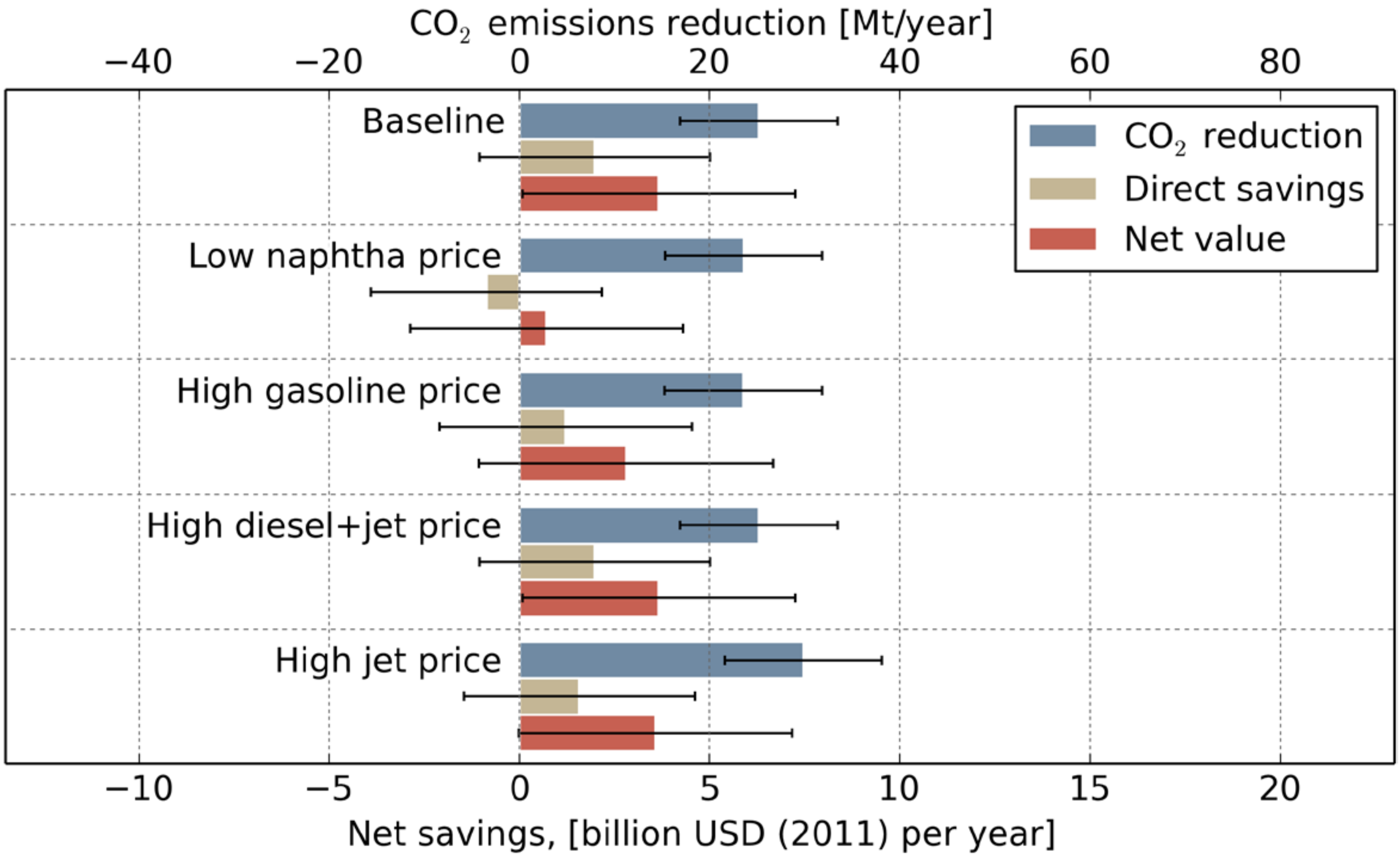
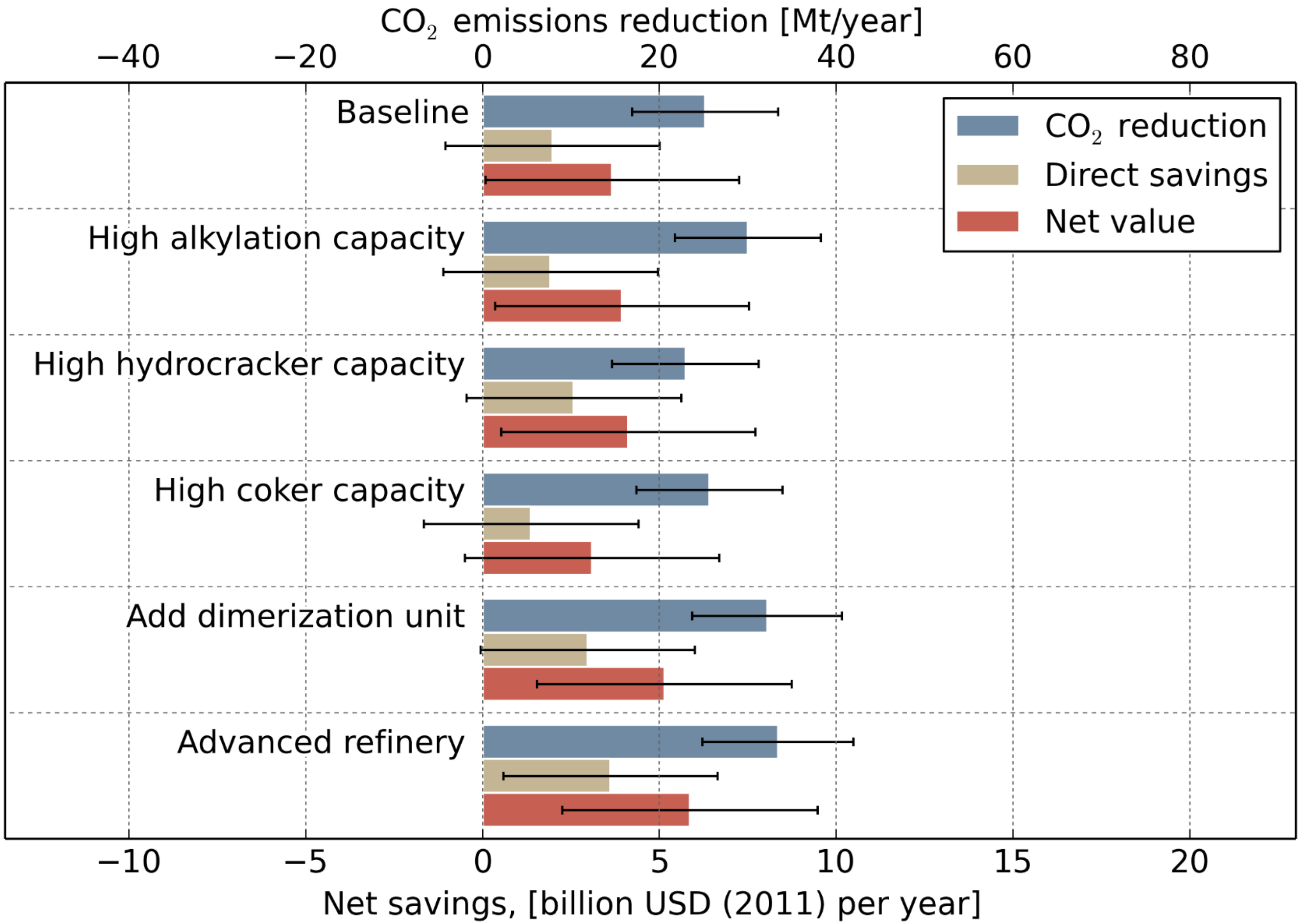
Sensitivity to Product Prices



Sensitivity to Refinery Configuration



Refinery Inputs & Outputs

	Base rate kbbl / day	Change kbbl / day	% Change
Crude Oil	100.0	-	-
Gasoline	55.0	-3.80	-6.9%
Ethanol	5.5	-0.25	-4.5%
Diesel	30.4	+0.89	+2.9%
Jet Fuel	9.8	-0.26	-2.6%
LPG	1.1	+0.48	+44.8%
Fuel Oil	5.3	-0.23	-4.4%
Light Naphtha	0.0	+1.52	-
Coke (BOE)	3.8	-0.0	-0.1%
Fuel Gas (BOE)	1.4	+0.01	+1.0%
Total (liquids)	**96.1**	**-1020**	**-1.1%**

Gasoline Blending Components

Component	10% Premium		80% Premium	
	vol. %	RON	vol. %	RON
Reformate	**24.3**	**94.6**	**24.4**	**102**
Alkylate	12.7	94.5	13.7	94.5
FCC Naphtha	10.8	93.7	16.7	93.8
Hydrotreated FCC Naphtha	26.4	90.7	22.1	90.8
Light Straight Run	**7.7**	**66.2**	**0.0**	**-**
Isomerate	**0.0**	**-**	**5.3**	**76.9**
Hydrocracked Naphtha	3.7	80.5	3.9	80.5
Coker Naphtha	3.0	65	2.1	65
Iso-butane	1.4	98.6	1.7	98.6
Ethanol	10.0	129	10.0	129

- Need RON increase of 4.2 points
- Baseline giveaway: 0.8 points
- Pool RON increased by 3.4 points
- Increased reformer severity: 1.8 points
- Isomerization of LSR: 0.6 points
- Exclusion of light naphtha: 0.7 points