Identification and Evaluation of Potential Best Practices for Greenhouse Gas Emissions Reductions in Freight Transportation

H. Christopher Frey, Ph.D.

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Department of Civil, Construction, and Environmental Engineering
North Carolina State University
Raleigh, NC 27695

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North Carolina State University

- "Research I" University
- Part of the UNC System
- 31,000 students
- 8,000 faculty and staff
- $315 million/yr in research
- 10 colleges
- Central campus in Raleigh, North Carolina

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Department of Civil, Construction, and Environmental Engineering

- 40 faculty
- 900 undergraduate students
- 250 graduate students

Energy and Environmental Research

- Measurement and modeling of activity, fuel use, and emissions of onroad and nonroad vehicles, using Portable Emission Measurement Systems (PEMS)
- Modeling and evaluation of advanced power generation and environmental control technologies
- Quantification of uncertainty in emission inventories
- Life cycle inventory and energy mix modeling of energy technologies and systems
- Environmental exposure and risk assessment
- Systems analysis methods for environmental models: variability, uncertainty, sensitivity, optimization

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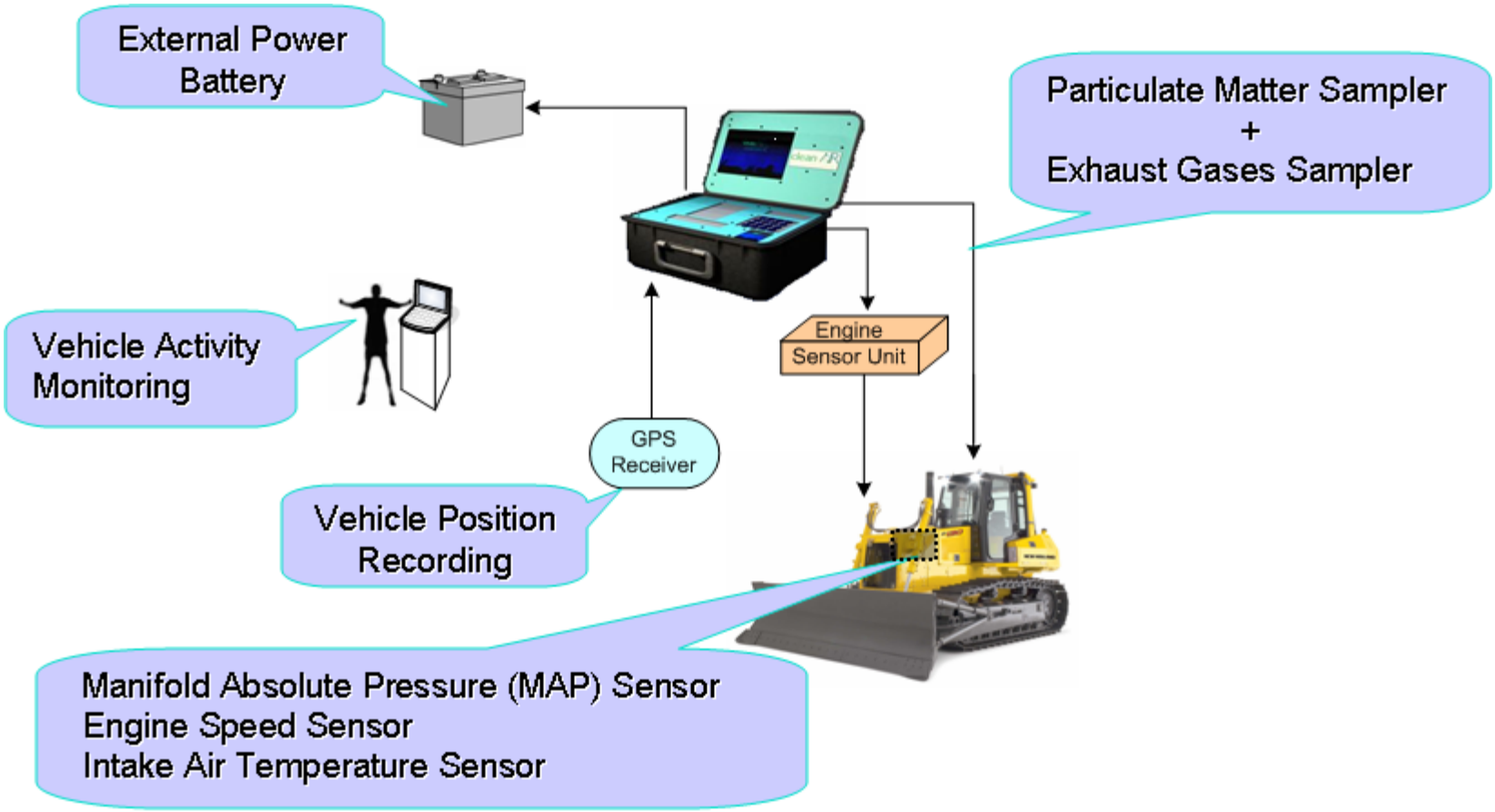
Real-World Field Measurement of Onroad and Nonroad Vehicle Activity, Fuel Use and Emissions Using a Portable Emission Measurement System (PEMS)



- Can be used with both onroad (e.g., cars, trucks) and nonroad (e.g., construction vehicles, locomotives) vehicles
- Have developed and applied methodologies for data collection for the last 8 years.
- Currently have two PEMS systems in active use, including evaluation of biofuels and additives

Related Research and Projects

- Measurement and Modeling of Real-World Vehicle Emissions
  - Development of Micro-scale and Modal Models of Fuel Use and Emissions Rates
  - Light Duty Gasoline Vehicles, Light Duty Diesel Vehicles, Heavy Duty Diesel Vehicles (e.g., dump trucks, combination trucks, cement mixers), Nonroad vehicles (e.g., backhoes, bulldozers, excavators, front-end loaders, motor graders, skid steer loaders, nonroad dump trucks)
  - Comparison of B20 versus petroleum diesel
  - Evaluation of fuel additive
  - Assessment of duty cycles
  - Comparison of engine certification tiers

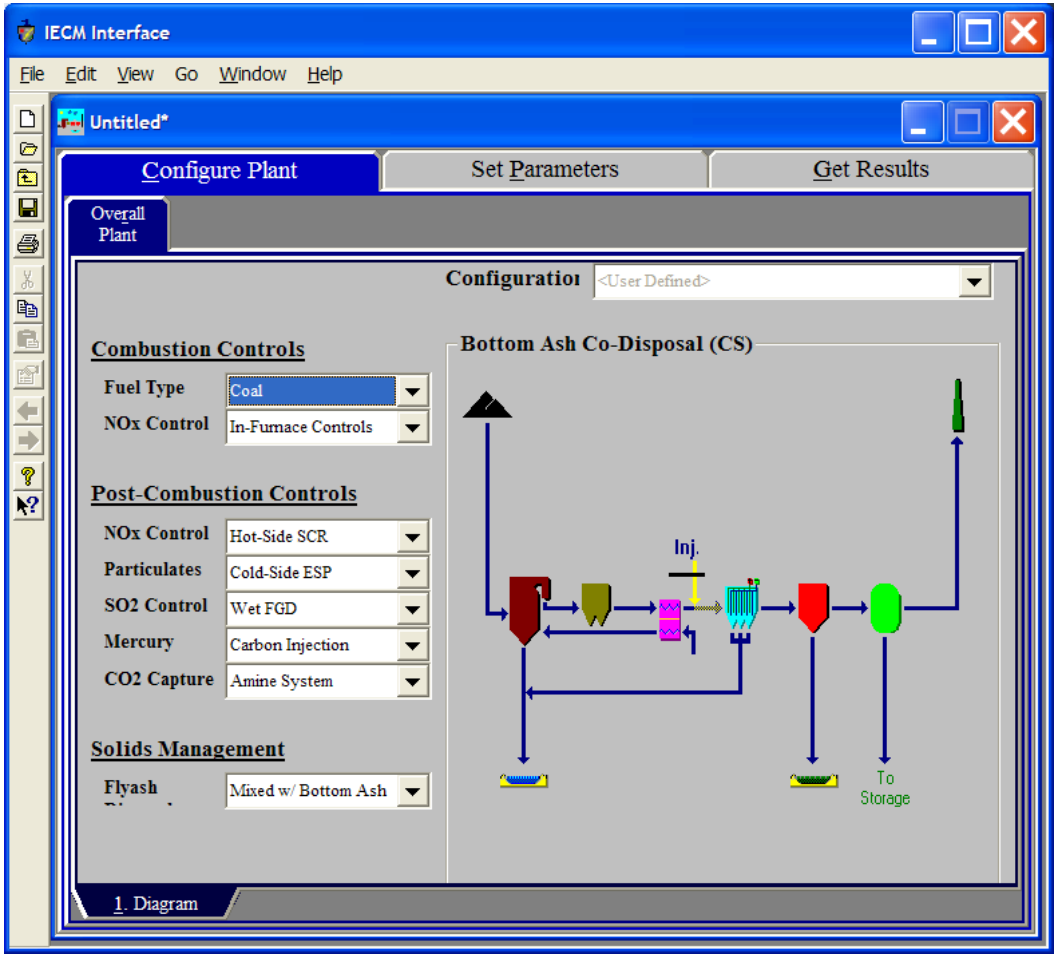
Related Research and Projects

- Assessment of auxiliary power units for long-haul sleeper cab freight trucks
  - Field data collection on 20 trucks for approx. 1 year in collaboration with Volvo
  - Detailed analysis of vehicle activity, fuel use, and emissions for APU and base engines
- Effect of Land-Use on Mobile Source Emissions
  - Assessment of land-use scenarios
  - Development of new modal emission modes for advanced vehicle technologies
  - Coupling of a travel demand model and new emissions models to estimate mobile source emissions inventory
- Life cycle inventory modeling for comparison of alternative fuels and vehicle technologies (e.g., biodiesel, ethanol, electric vehicles)
- Evaluation of highway emissions on near-roadway air quality

Process Simulation Modeling Capabilities

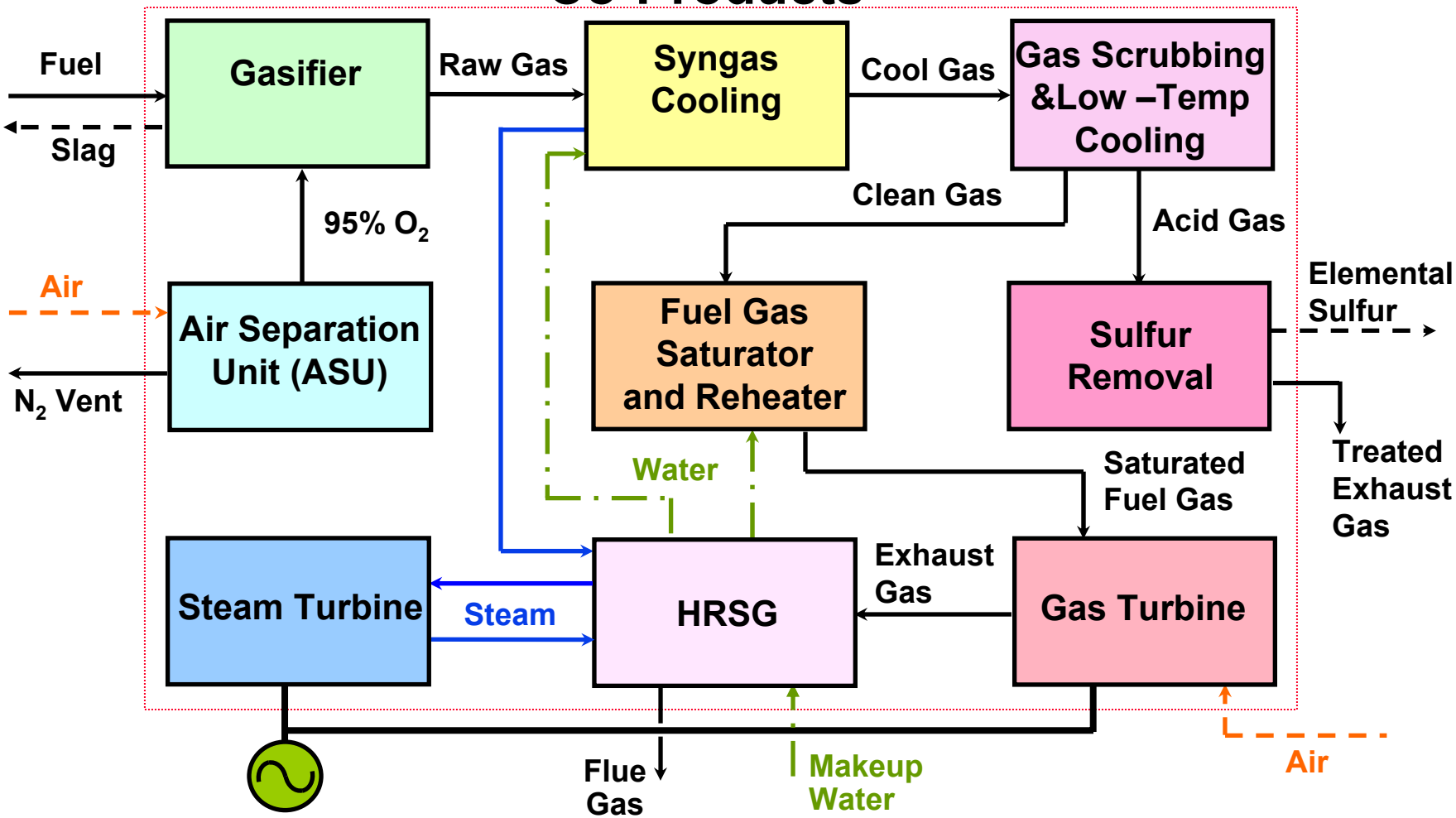
Development and application of process simulation models for:

- Gasification of fossil and non-fossil fuels
- Syngas cleanup
- Power generation (e.g., gas turbine systems)
- By-product recovery (e.g., sulfur)
- Co-production (e.g., methanol, ammonia)
- Benchmark comparisons based on models of conventional power generation (e.g., coal-fired furnace power plants, natural gas-fired gas turbines)



Integrated Environmental Control Model, shown above, for combustion-based power generation systems

Process Simulation Modeling of Efficiency, Performance, Emissions, and Cost of Advanced Systems for Power and Co-Products



HRSG: Heat Recovery Steam Generator

- Example of a gasification combined cycle system flowsheet modeled using ASPEN Plus
- Unique capabilities for quantification of uncertainties in new technologies and optimization of process configuration and design parameters under uncertainty

Objectives

- Identify and characterize potential best practices for reduction of greenhouse gas (GHG) emissions from the freight transportation sector
- Quantify and compare the potential reductions in GHG emissions
- Analyze cost effectiveness of each best practice if quantitative cost information is available
- Develop a guidebook regarding these best practices

Outline

- Definition of Key Concepts
- Study Methodology
- List of Best Practices
- Total Modal GHG Emissions Reductions
- Comparisons of Best Practices Whose Costs Are Assessed Quantitatively
- Inter-modal Substitutions
- Overview of the Guidebook
- Conclusions and Recommendations

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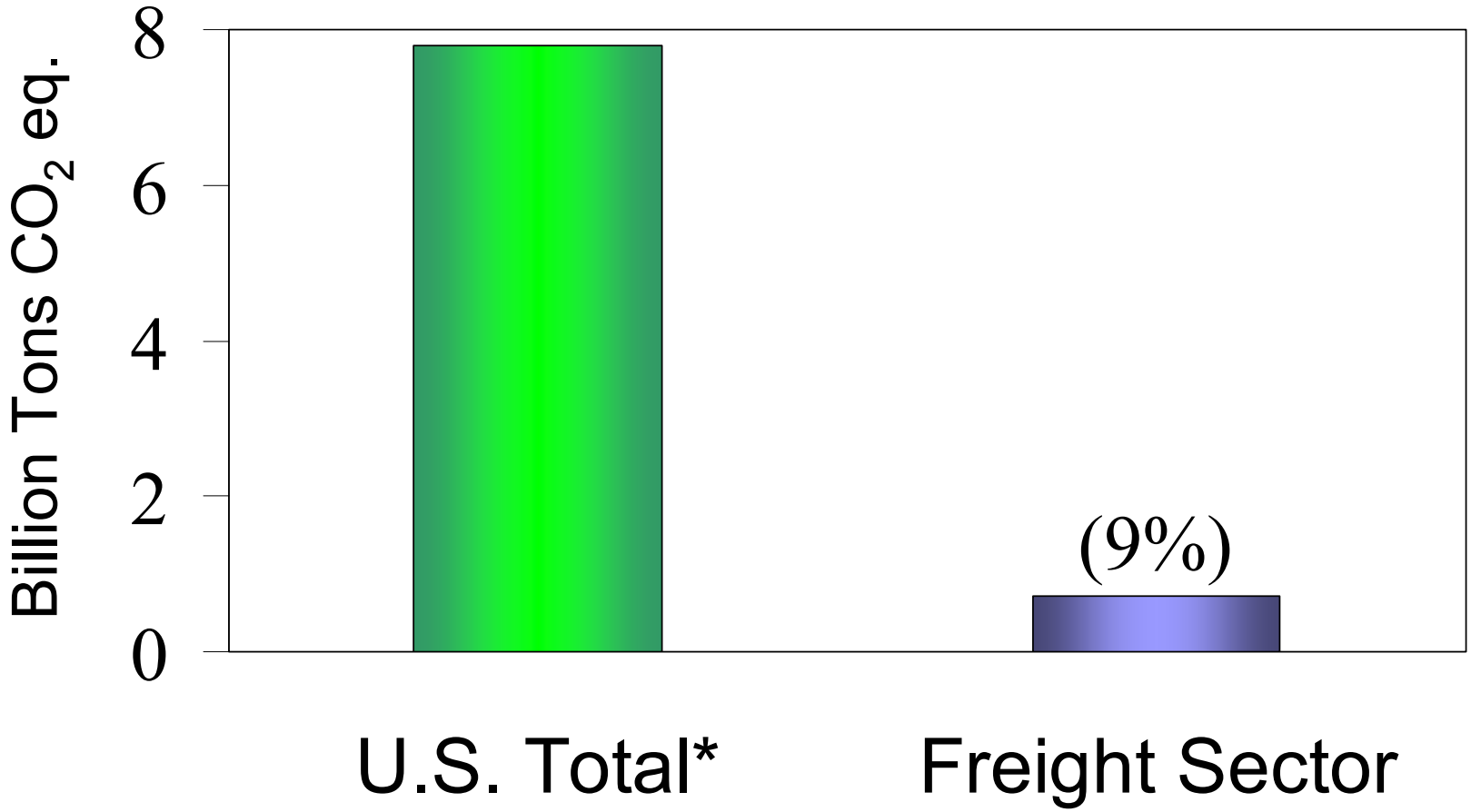
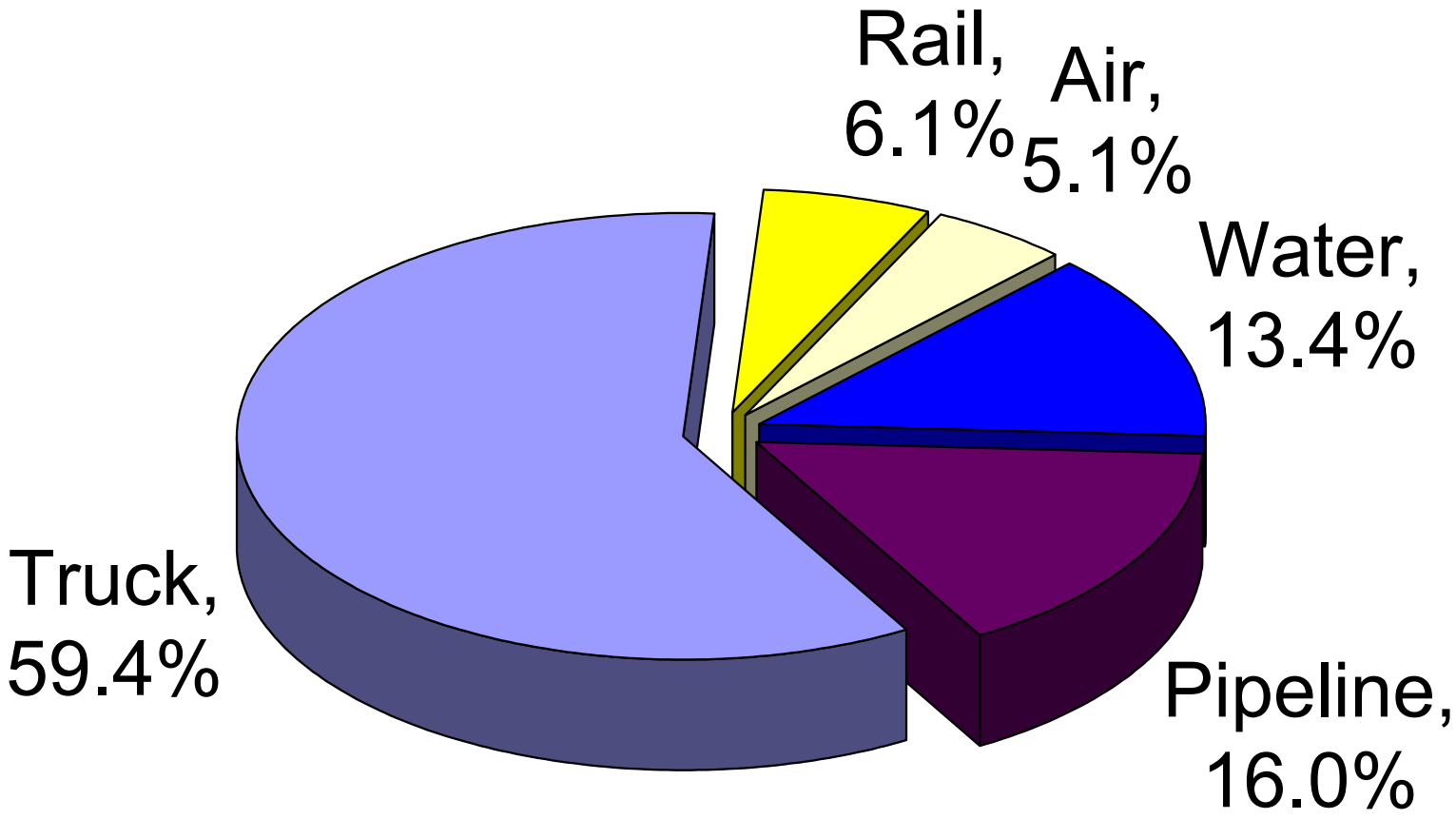
GHG Emissions in U.S. Freight Transportation, 2003



*U.S. Total includes bunker fuel for international aviation and marine

Distribution of GHG Emissions by Mode within the U.S. Freight Sector, 2003



Total GHG Emissions: 7.20×10^8 Tons CO_2 Equivalent

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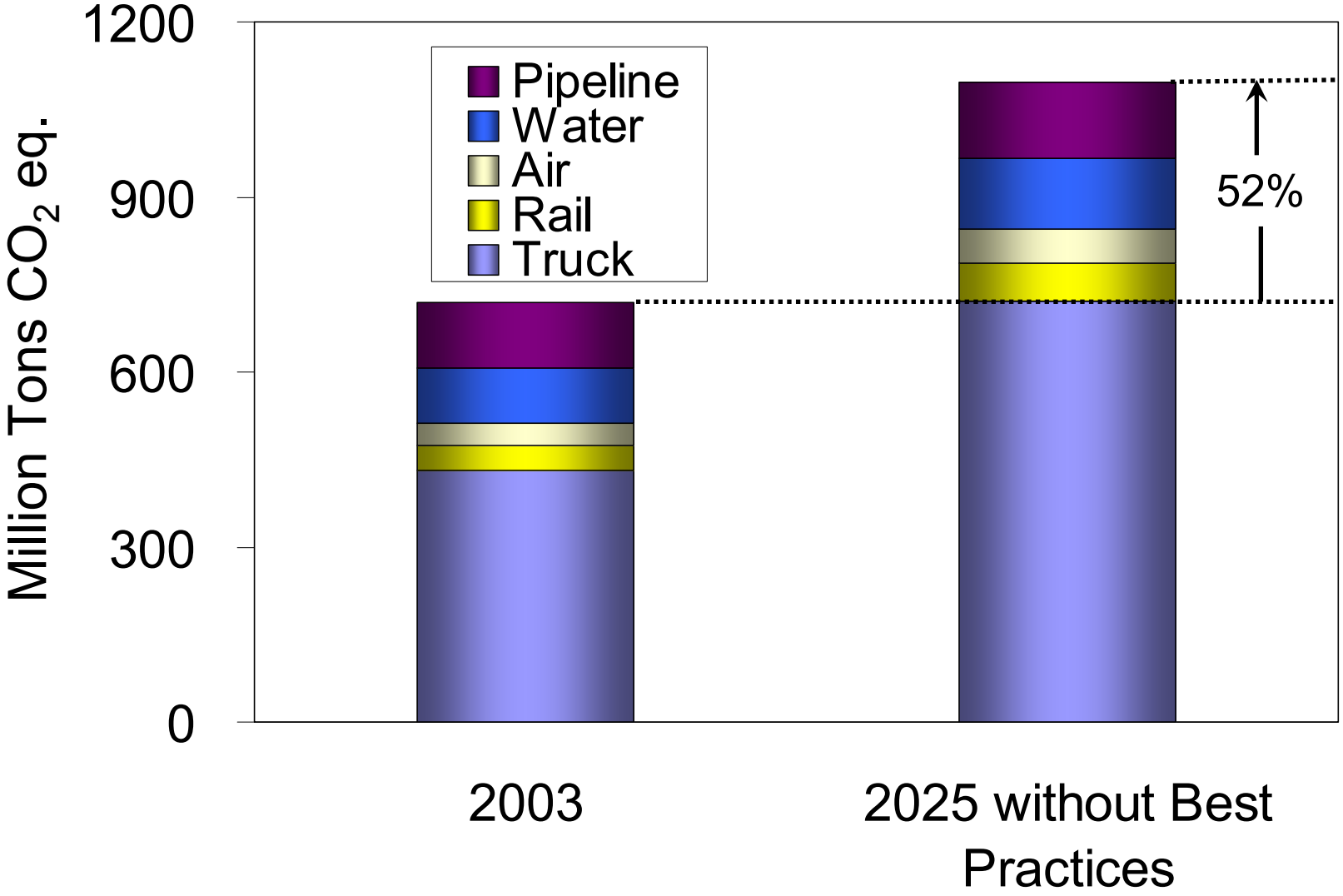
Estimated Baseline GHG Emissions from Freight Transportation from 2003 to 2025



Definitions and Concepts

Best Practices:

- Technological or operational strategies
- Existing or developing
- Reduce GHG emissions
- Reduce energy use or increase use of alternative fuels
- Reduce refrigerant leakage or increase use of low Global Warming Potential (GWP) refrigerants

Definitions and Concepts

Subgroup:

- A collection of best practices in a mode that have either similar objectives or methods

Greenhouse Gas Emissions:

- Focus on CO_2, CH_4, and hydrofluorocarbons (HFCs)
- Global Warming Potential (GWP):

  GWP = 1 for CO_2

  GWP = 21 for CH_4

  GWP = 1,300 for HFC-134a

Developmental Status: New concepts, pilot tests, and commercially available systems

Study Methodology

(1) Identify *potential* best practices (BPs) based on literature review

(2) Assess maximum reductions in 2025 GHG emissions and energy or refrigerant use

(3) Assess cost savings (where data are available)

(4) Summarize and report assessment results

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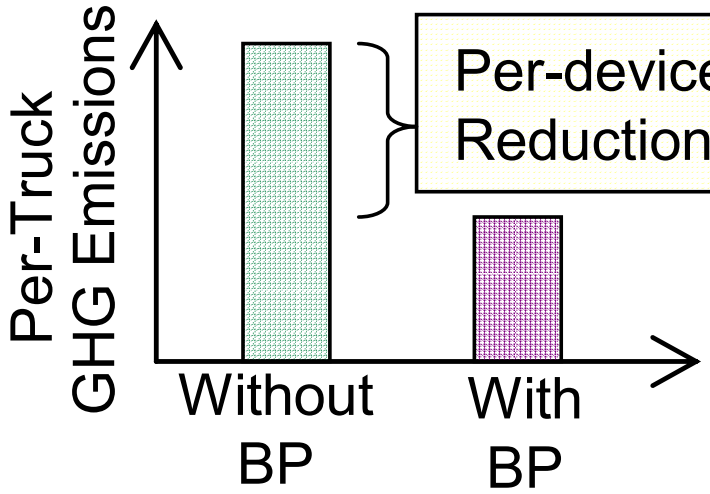
Assessment of Potential GHG Emissions Reductions for Individual Best Practices



Per-device Reductions (%)

Fraction of modal activity to which a BP is applicable

Best estimate of maximum market penetration rate by 2025

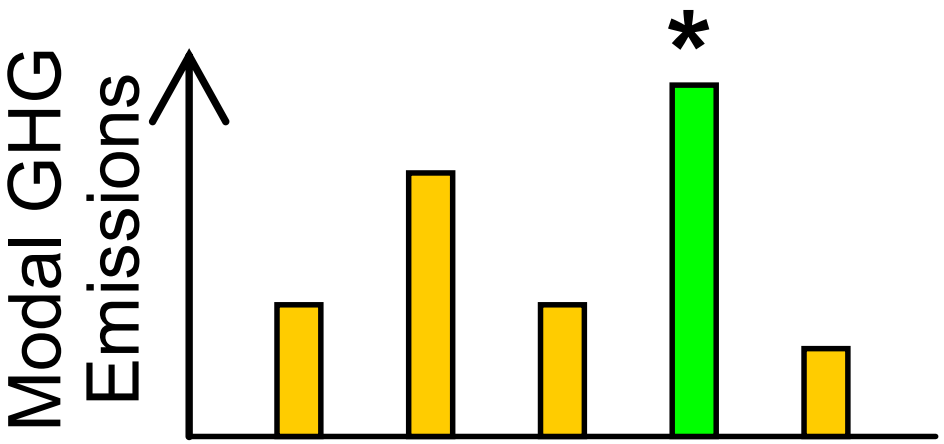
Modal Reductions by 2025 (%)

**Life cycle inventories were assessed for alternative fuels*

Assessment of Potential GHG Emissions Reductions for Multiple Best Practices

Aggregate reductions for a subgroup:

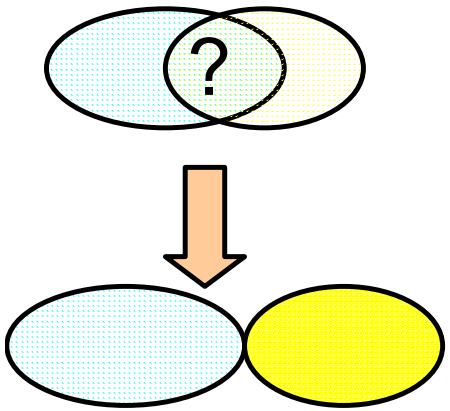
- Linear combination of individual best practices
- Mutual exclusion
  - Some BPs cannot be used simultaneously
  - Based on BP with the highest reduction potential
  - The estimates do not double count mutually exclusive BPs



Assessment of Potential GHG Emissions Reductions for Multiple Best Practices

Aggregate reductions for a subgroup:

- Interaction:
  - Some BPs can be used together but interact
  - Quantification of interaction is unknown or not reported
  - Used a linear combination as an estimate
  - May overestimate the maximum possible reduction for the subgroup



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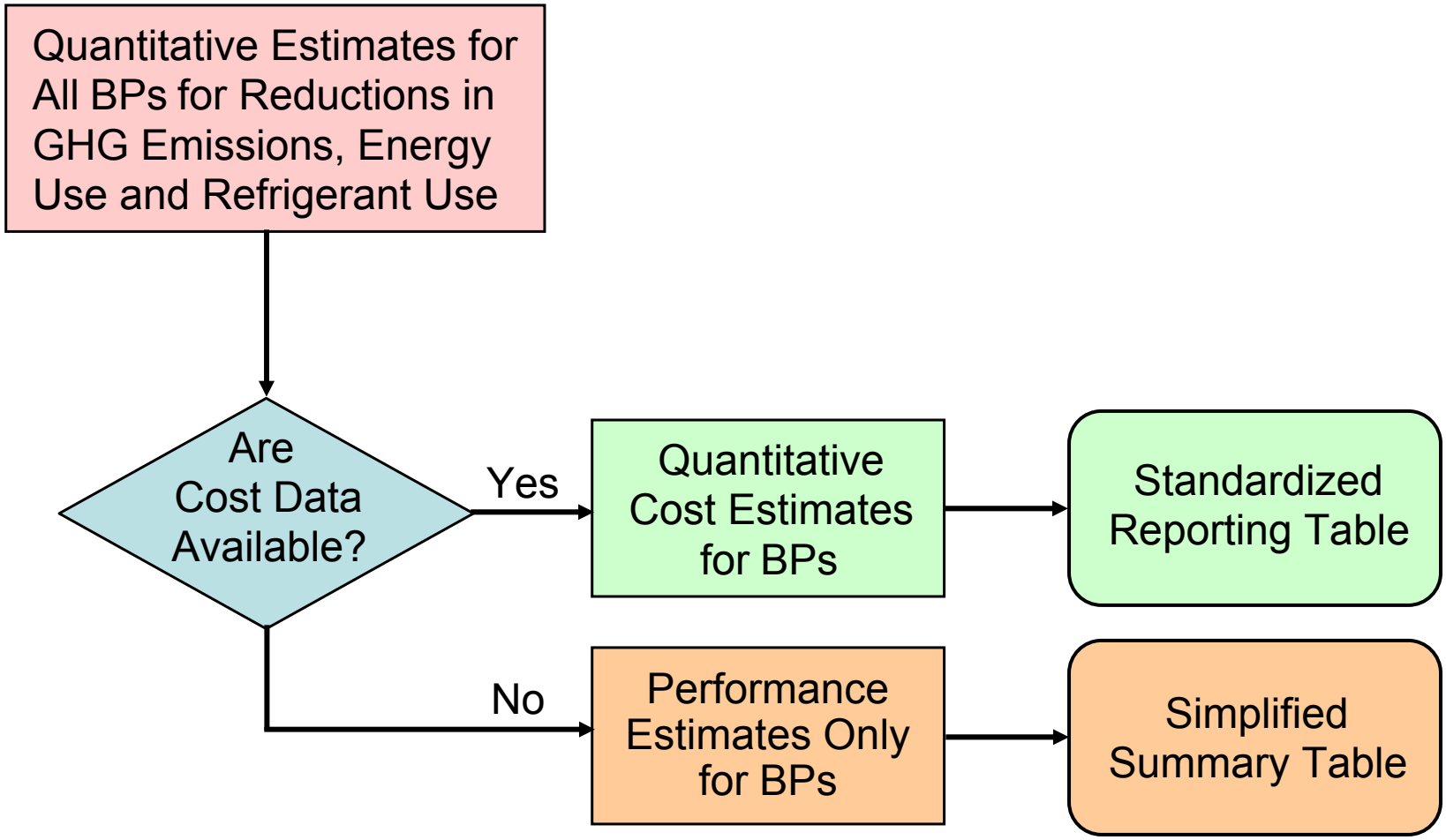
Assessment of Best Practices With or Without Cost Data



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Summary of Best Practices for Freight Transportation

A total of 59 potential best practices have been identified

Mode	Number of Best Practices	Names of Subgroup
Truck	33	Anti-idling; Air Conditioning System Improvement; Aerodynamic Drag Reduction; Tire Rolling Resistance Improvement; Hybrid Propulsion; Weight Reduction; Transmission Improvement; Diesel Engine Improvement; Accessory Load Reduction; Driver Operation Improvement; Alternative Fuel
Rail	6	Anti-idling; Weight Reduction; Rolling Resistance Improvement; Alternative Fuel
Air	10	Aerodynamic Drag Reduction; Air Traffic Management Improvement; Weight reduction; Ground Support Equipment Improvement; Engine Improvement
Water	5	Propeller System Improvement; Anti-idling; Alternative Fuel
Pipeline	5	Process Control Device Improvement; Connecting Method; Maintenance

Example: Auxiliary Power Units

- Auxiliary power units (APUs) :
  - An example of an anti-idling technique
  - Small diesel engine-generator to reduce fuel use
  - Supply power for electrical air conditioning, heating, and auxiliary loads

Source: Mechron Power Systems
http://www.ccslightning.com/

Key Inputs for Quantitative Assessment (Example: Auxiliary Power Units)

Source: Volvo Trucks North America, www.volvo.com/trucks/na/en-us/

- Truck Base Engine Idle Fuel Use: 0.85 gal/hr
- APU fuel use: 0.2 gal/hr
- Idle hours: 1,830 hours/year
- APU capital cost: $8,279 per device
- APU maintenance cost: $460/year
- APU lifetime: 5 years
- Diesel fuel price: $2.56/gallon

Assessment of GHG Emissions and Energy Use Reduction (Example: Auxiliary Power Units)

- Quantitative Assessment for Reductions in GHG Emissions and Energy Use

Standardized Reporting Table for Expected Reductions, 2025

Variable	Unit	Value
Annual ton-miles for the mode	10^9 ton-miles/year	2,098
Annual ton-miles to which a practice is applicable	10^9 ton-miles/year	453
Annual GHG emissions reduction	10^6 ton CO_2 eq./year	15.0
Annual energy use reduction	10^{12} BTU/year	185.0
Unit GHG emissions reduction	10^{-3} lb CO_2 eq./ton-mile	66
Unit energy use reduction	BTU/ton-mile	409

Quantitative Cost Assessment (Example: Auxiliary Power Units)

- Quantitative Cost Assessment

Standardized Reporting Table for Expected Practice Costs and Cost Savings, 2025

Variable	Unit	Value
Capital cost	10^6 USD ($)	9,400
Annual O & M cost	$ 10^6 /year	520
Annualized cost	$ 10^6 /year	2,990
Annual energy cost saving	$ 10^6 /year	3,430
Net savings	$ 10^6 /year	440
Net savings per unit of GHG emissions reductions*	$/ton CO_2 eq.	29
Net savings per unit of energy use reduction*	$/$10^6$ BTU	2.3
Simple payback period	years	3.2

*Positive values denote cost savings

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Example of Details for Individual Potential Best Practices

Subgroup	I.D. No.	Brief Name of Best Practice	Developmental Status [a]	Potential Per-device Reductions in GHG Emissions (%)[b]	Potential Per-device Reductions in Energy Use (%)[b]	Potential Reductions in Modal GHG Emissions (%)[c]	Potential Reductions in Modal Energy Use (%)[c]	Percentage Contribution of a Subgroup to Total Reductions in Modal GHG Emissions (%)[d]	Percentage Contribution of a Subgroup to Total Reductions in Modal Energy Use (%)[d]	Potential Aggregate GHG Emission Reduction in 2025 for Each Subgroup (10^6 Tons CO_2 eq.)[e]	Potential Aggregate Energy Use Reduction in 2025 for Each Subgroup (10^{15} BTU)[e]
Anti-Idling	1-1	Off-Board Truck Stop Electrification	C	1.53	1.45	0.33	0.31	3.64	4.50	15.00	0.19
	1-2	Truck-Board Truck Stop Electrification	C	1.83	1.88	0.39	0.41				
	1-3	Auxiliary Power Units	C	9.62	9.87	2.08	2.13				
	1-4	Direct-Fired Heaters	C	4.85	5.00	1.05	1.08				
	1-5	Direct-Fired Heaters with Thermal Storage Units	P	13.33	13.74	2.88	2.97				

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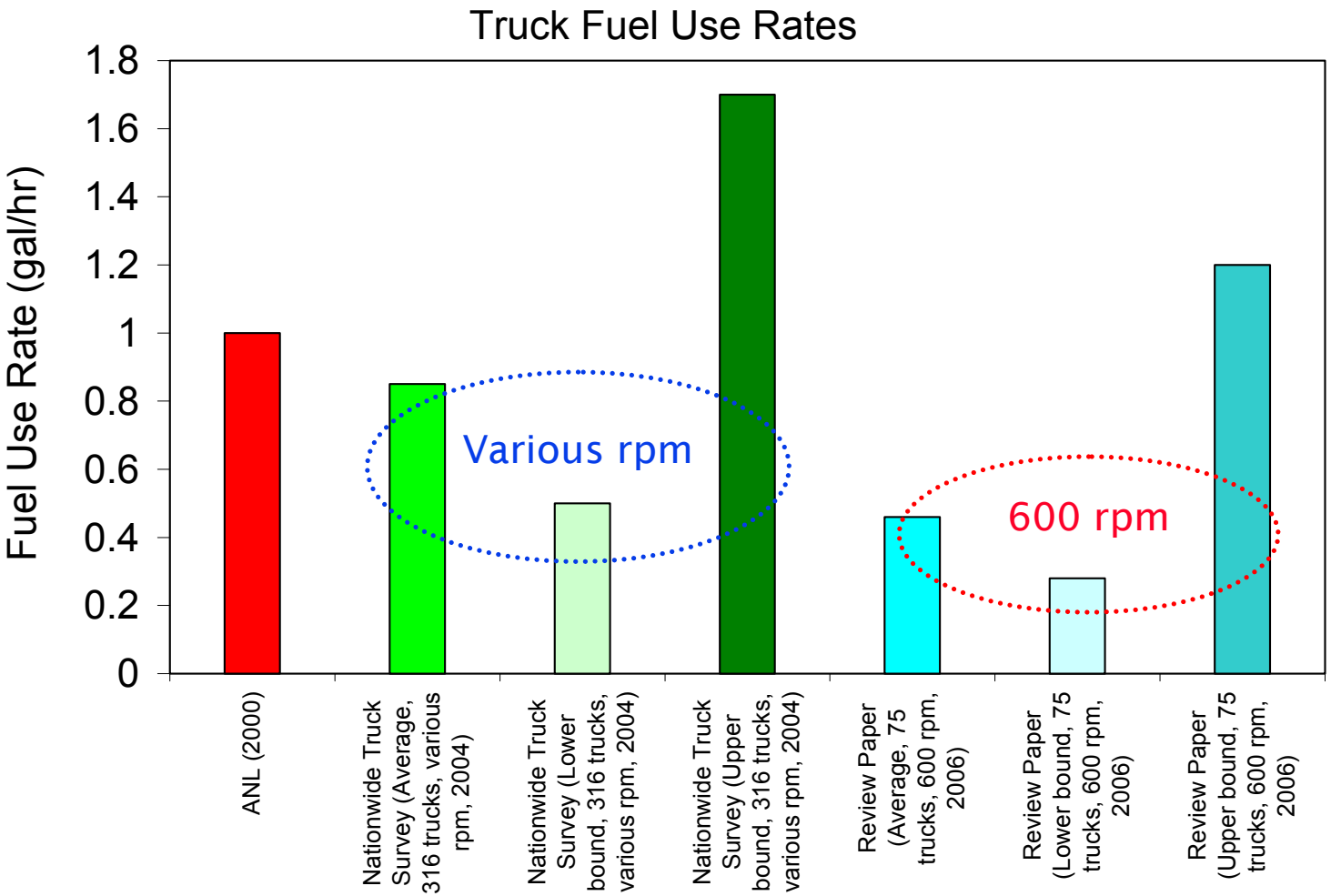
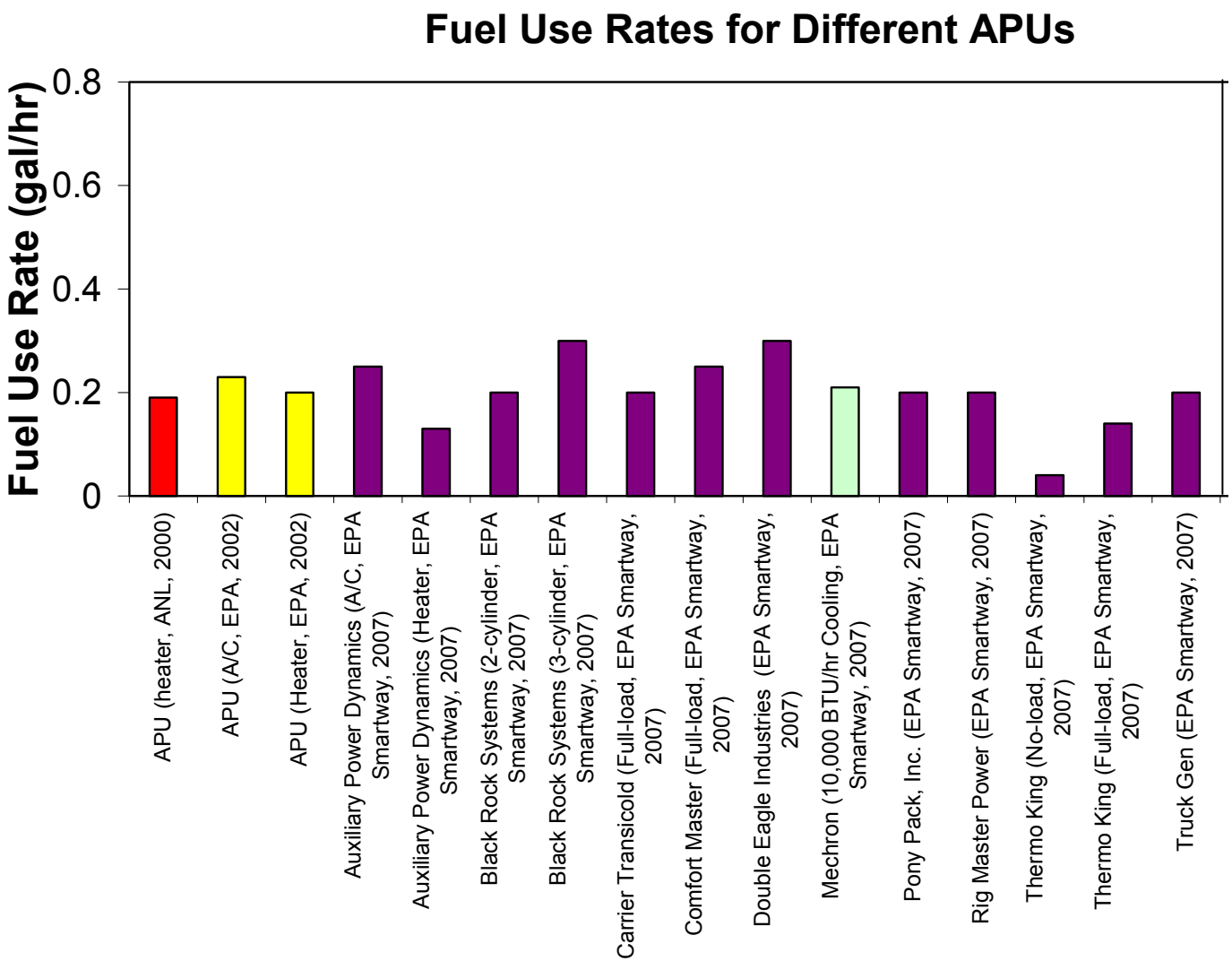
Variability in Key Inputs (Example: Truck Idle Fuel Use Rates)



Variability in Key Inputs (Example: APUs Fuel Use Rates)



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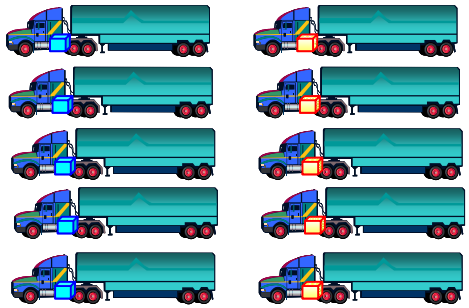
NCSU and Volvo Mobile Idle Reduction Project: Study Design and Data Acquisition System

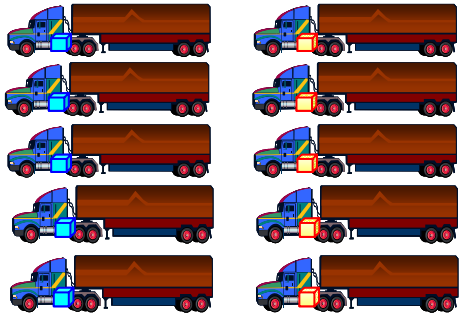
10 Fleet-A Trucks



With APU-A With APU-B

Average In-service time: 9,100 hours (as of 10/31/07)

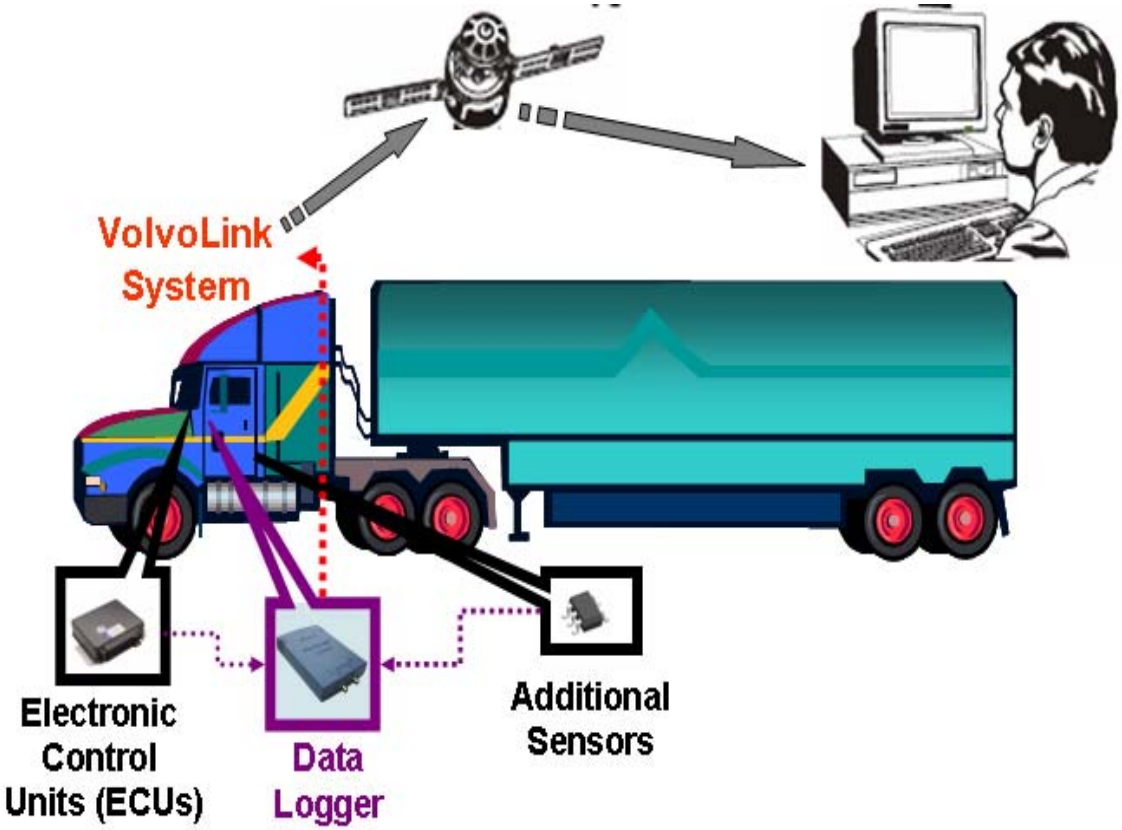
10 Fleet-B Trucks



With APU-A With APU-B

Average In-service time: 5,700 hours (as of 10/31/07)

Data Acquisition System



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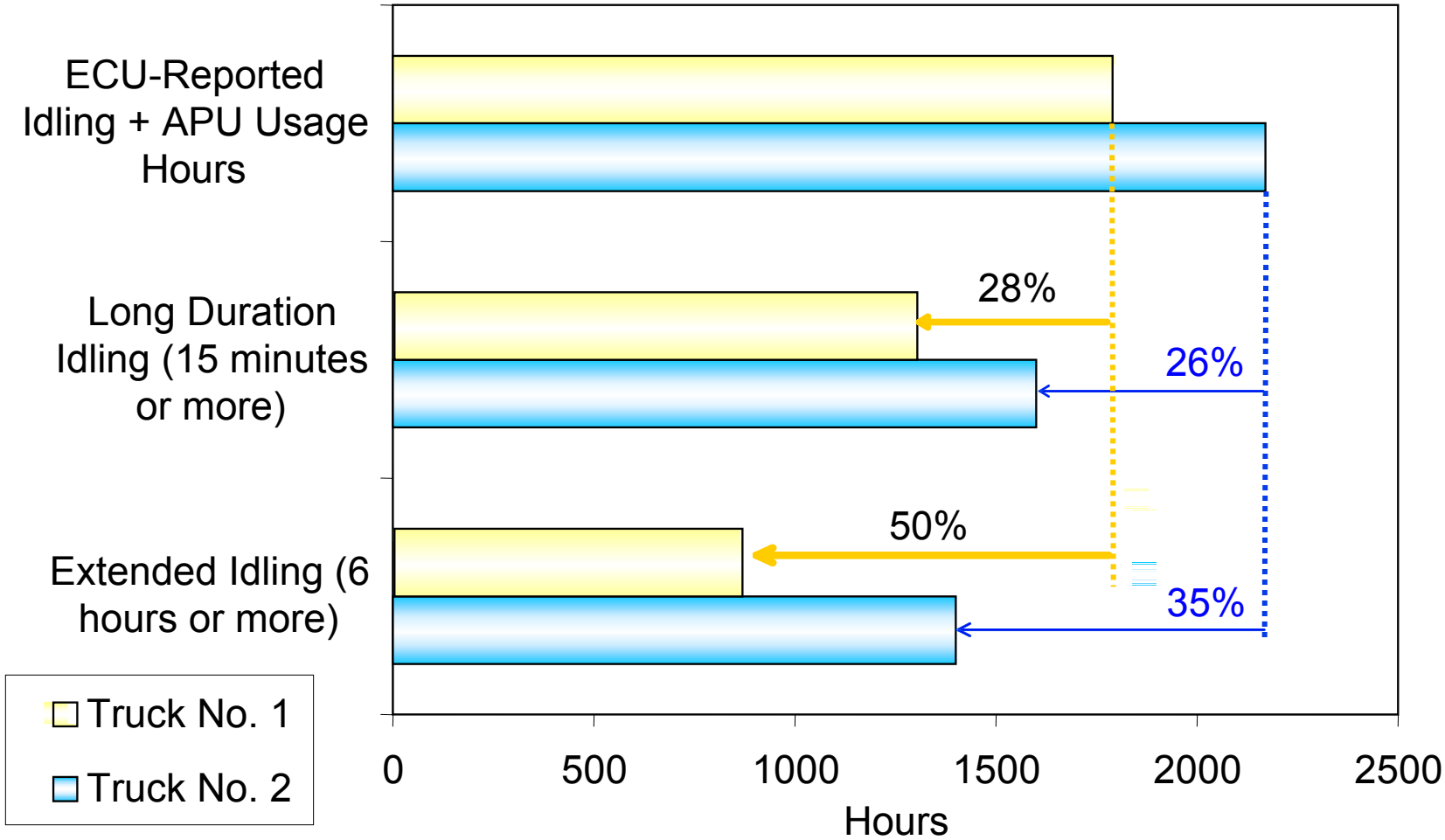
Quantification of Long-Haul Truck Stop Activities

Comparisons of Idling, Long-Duration Idling and Extended Idling by an Annual Basis



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Results of Portable Emision Measurement System Tests of Base and APU Engines

Fuel Use Rates for the Base and APU Engines:

- Base engine idle fuel use rate data from 20 field trucks:
  Average of 0.45-0.6 gal/hr depending on ambient temperature
- APU fuel use rate data measured in bench tests

Fuel Use Rate and Emission Factors for the Base and APU Engines:

Base Engine:

Fuel Use (gal/hr)	NO (g/hr)	HC (g/hr)	CO (g/hr)	CO_2 (kg/hr)	PM (g/hr)
0.45	69.2	2.7	12.8	4.6	1.1
0.60	92.2	3.6	17.1	6.1	1.4

APU-A:

Electrical Load (kW)	Fuel Use (gal/hr)	NO (g/hr)	HC (g/hr)	CO (g/hr)	CO_2 (kg/hr)	PM (g/hr)
0	**0.28**	5.1	1.4	23.3	2.8	0.9
3	**0.45**	16.2	1.6	11.3	4.5	1.5

APU-B:

Electrical Load (kW)	Fuel Use (gal/hr)	NO (g/hr)	HC (g/hr)	CO (g/hr)	CO_2 (kg/hr)	PM (g/hr)
0	**0.22**	11.2	1.4	7.5	2.3	0.7
3	**0.45**	24.7	0.8	5.7	4.6	1.5

Preliminary Estimates for Cumulative Avoided Fuel Use and Emissions: Examples

Truck No.	Fuel Saved (gal)	Avoided NO Emission (kg)	Avoided HC Emission (g)	Avoided CO Emission (g)	Avoided CO_2 Emission (kg)	Avoided PM Emission (g)
1	64	21	505	-869	659	71
2	344	119	2795	-5436	3517	326
11	2	1	17	-98	23	2
17	100	26	713	2892	1013	130

Truck	Fleet	Predominant Idle Activity	Cumulative Total Hours in Service
1	A (Single Driver)	Base Engine	10,000
2	A (Single Driver)	APU	9,900
11	B (Team Drivers)	Base Engine	6,000
17	B (Team Drivers)	APU	6,400

Site-Specific Variability

- The actual fuel savings, emissions reductions, and cost for APUs (and other best practices) can be highly variable depending on specific situations.
- The results here provide comparisons based on typical, but not necessarily site-specific, values.
- There is a need for a tool to enable users to identify, compare, and evaluate potential best practices using relevant data.

Example of Assessment of Life Cycle Inventory and Real World Tailpipe Emissions for Soy-Based B20 vs. Petroleum Diesel

- Life cycle inventory comparison of fuels
- Geospatial implications of biofuel use
- Real-world implications for tailpipe emissions for 35 diesel engines
  - 12 dump trucks
  - 8 cement mixer trucks
  - 15 nonroad construction vehicles

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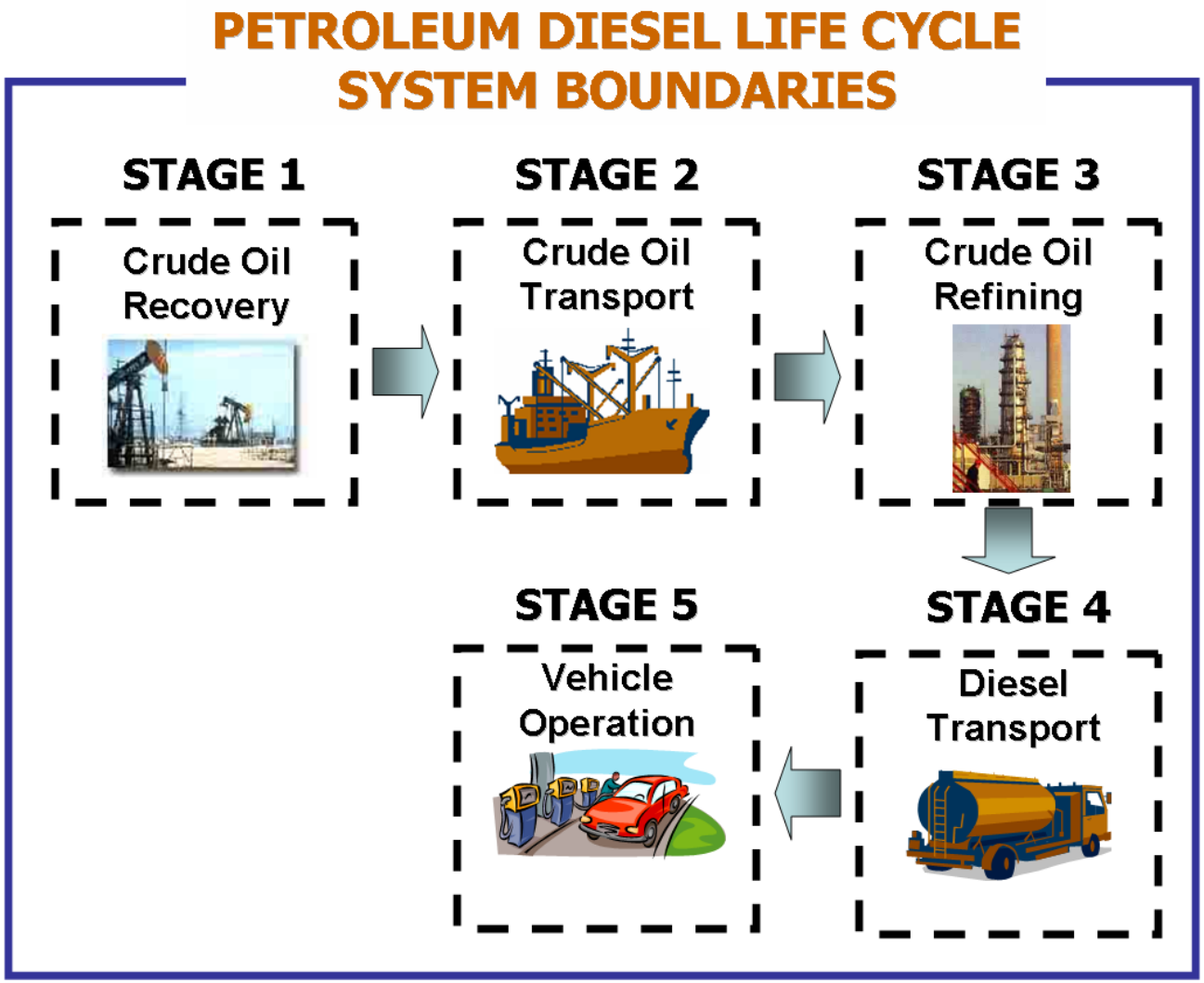
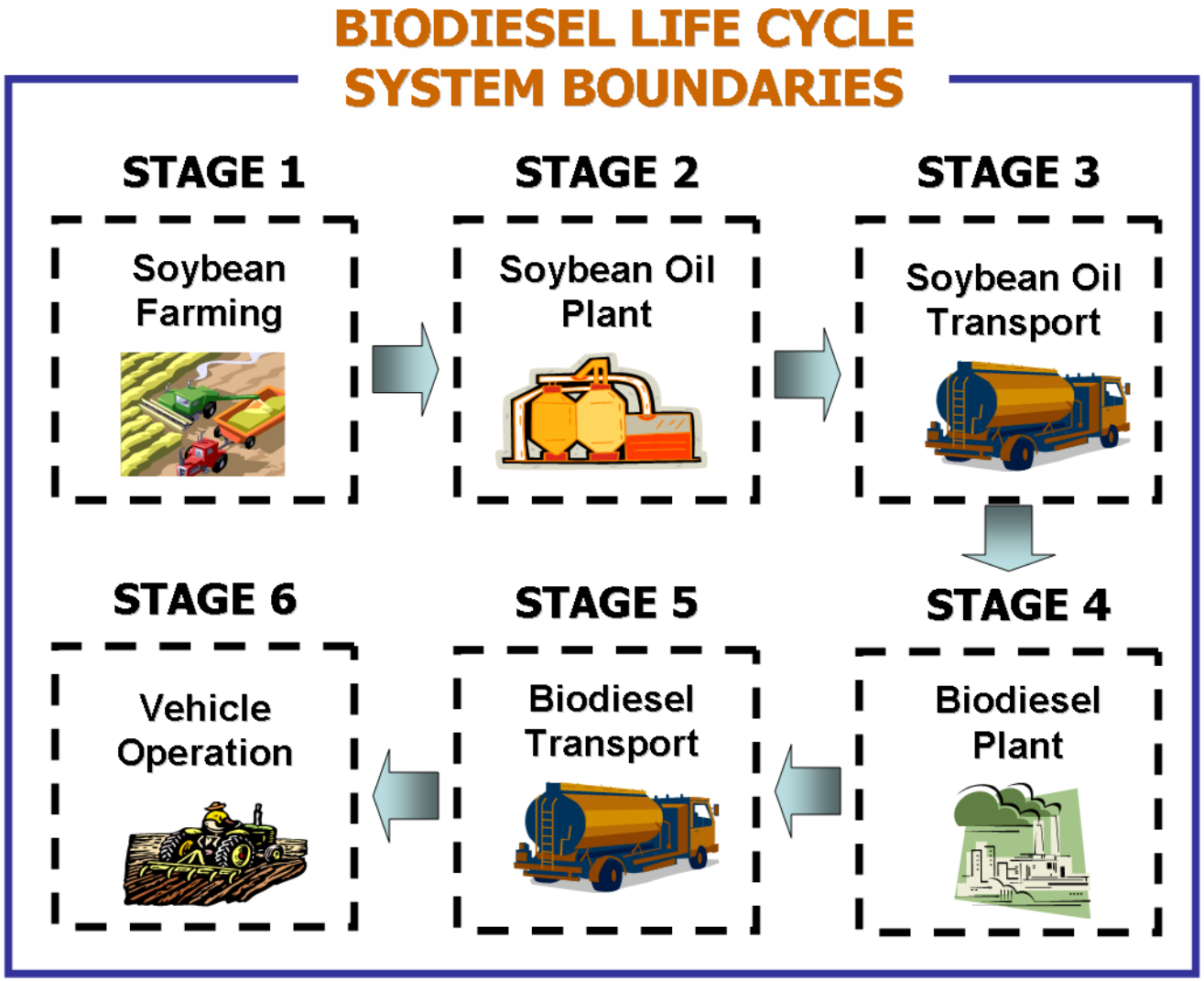
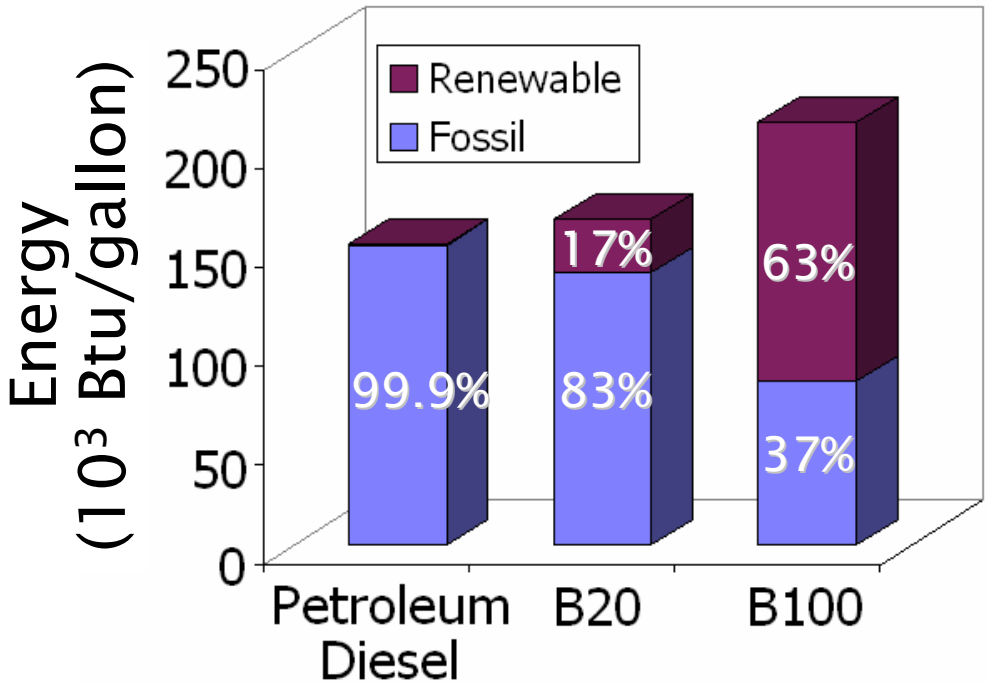
System Boundary of Petroleum Diesel Life Cycle



System Boundary of Biodiesel Life Cycle



Life Cycle Energy Use



The total energy includes the heating value of fuel itself and process energy. Biodiesel is considered as renewable energy.

0.07% of diesel transport fuel is biodiesel.

Reduction in LCI Fossil Energy:

B20: 9.1%

B100: 45.3%

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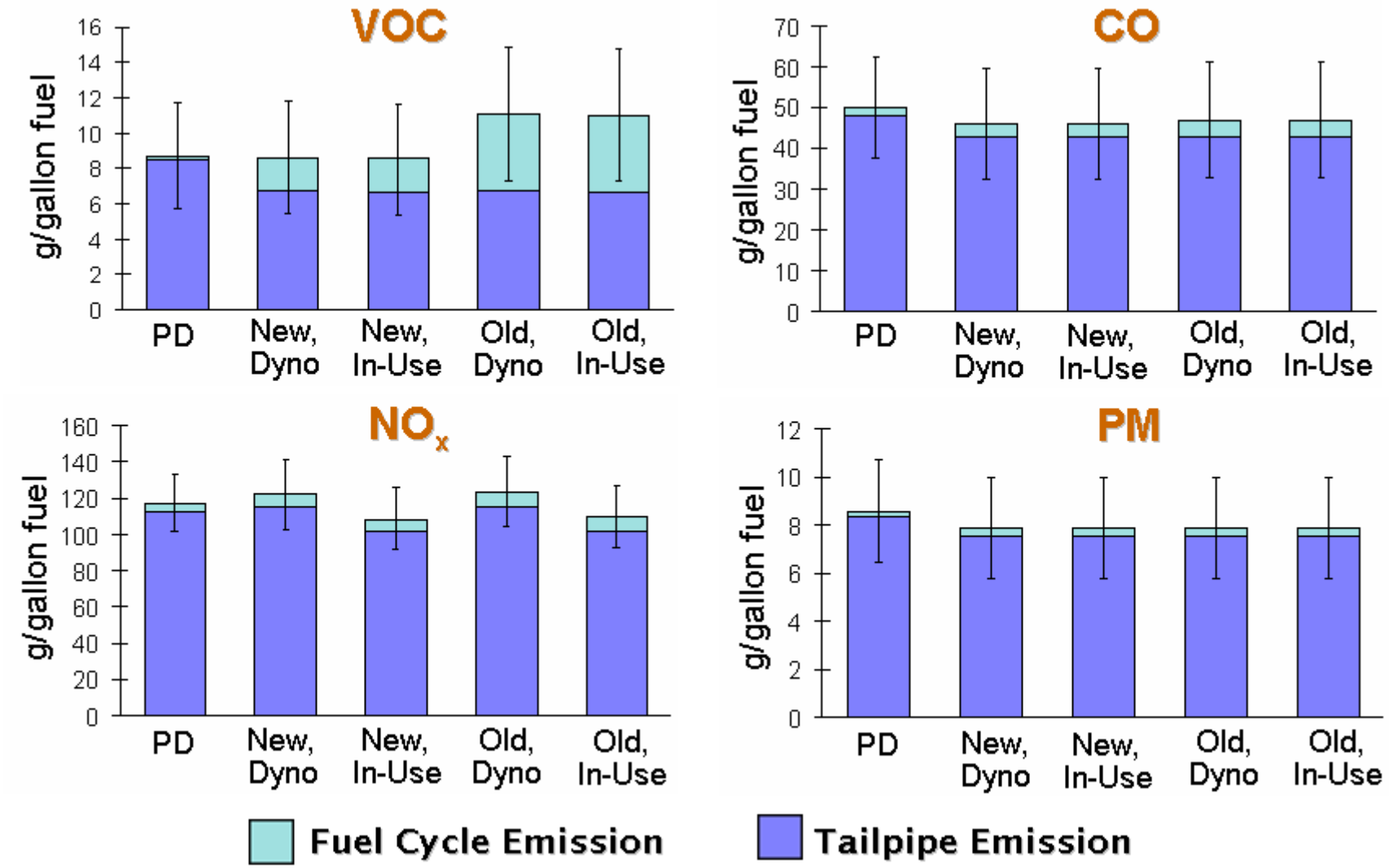
PD and B20 Life Cycle Emissions (Five Scenarios)



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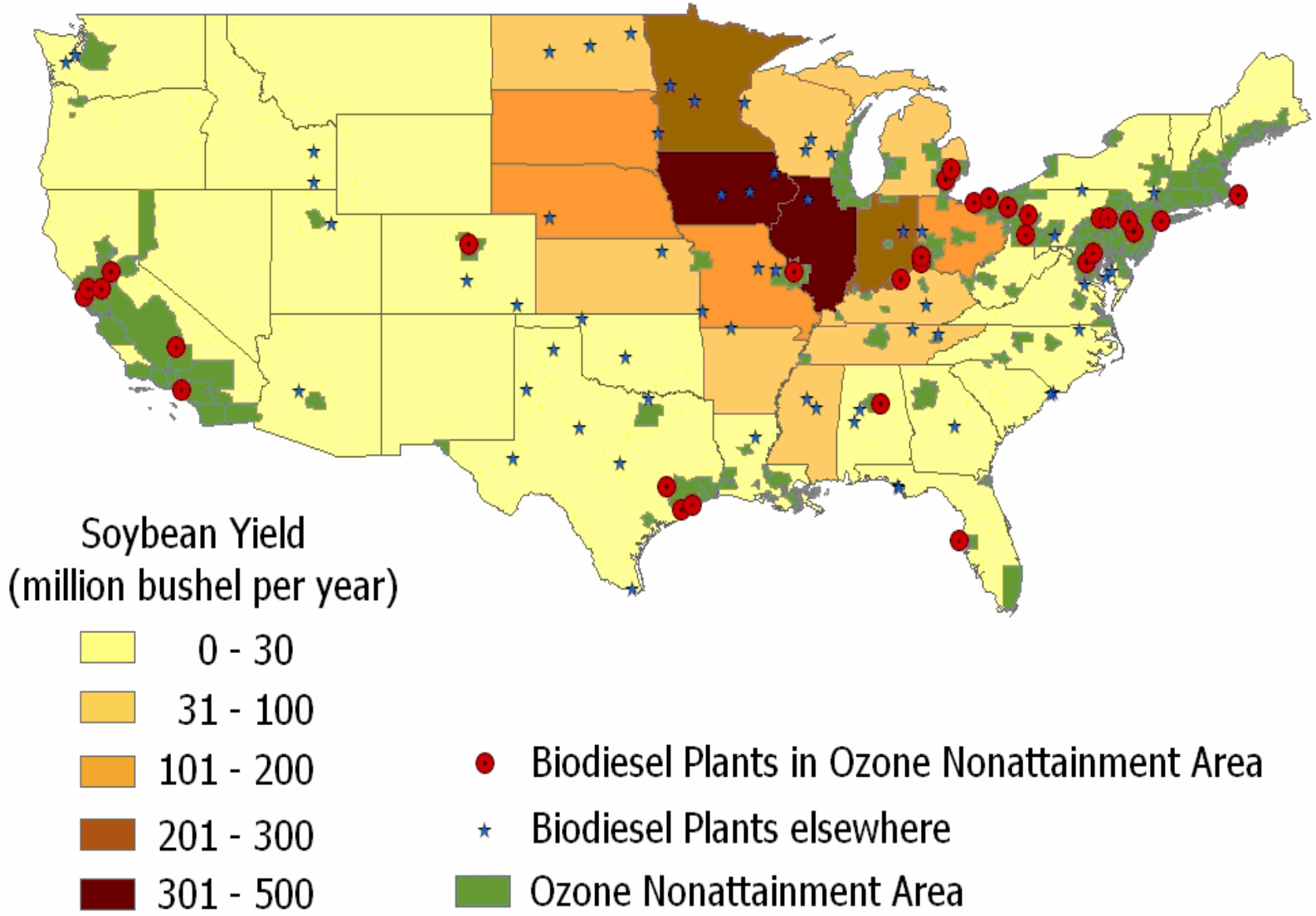
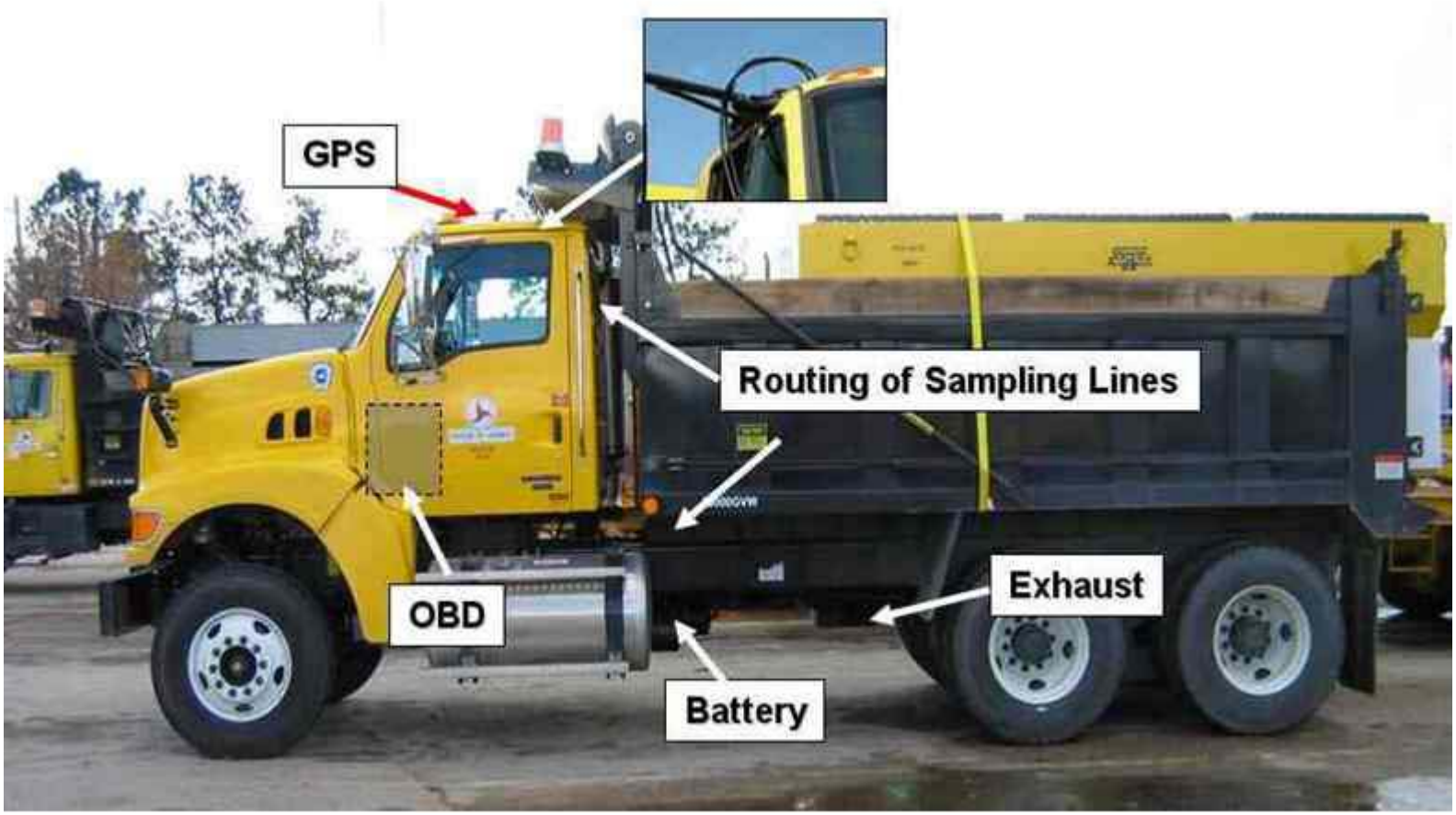
Soybean Yield, Biodiesel Plants and Air Quality in the US



Vehicle in Motion with Instrumentation



Tested Vehicles

Vehicle Type	Number Tested	
Single – Tier 1	4	
Single – Tier 2	2	
Tandem – Tier 1	4	
Tandem – Tier 2	2	

All vehicles are part of NCDOT Division 5

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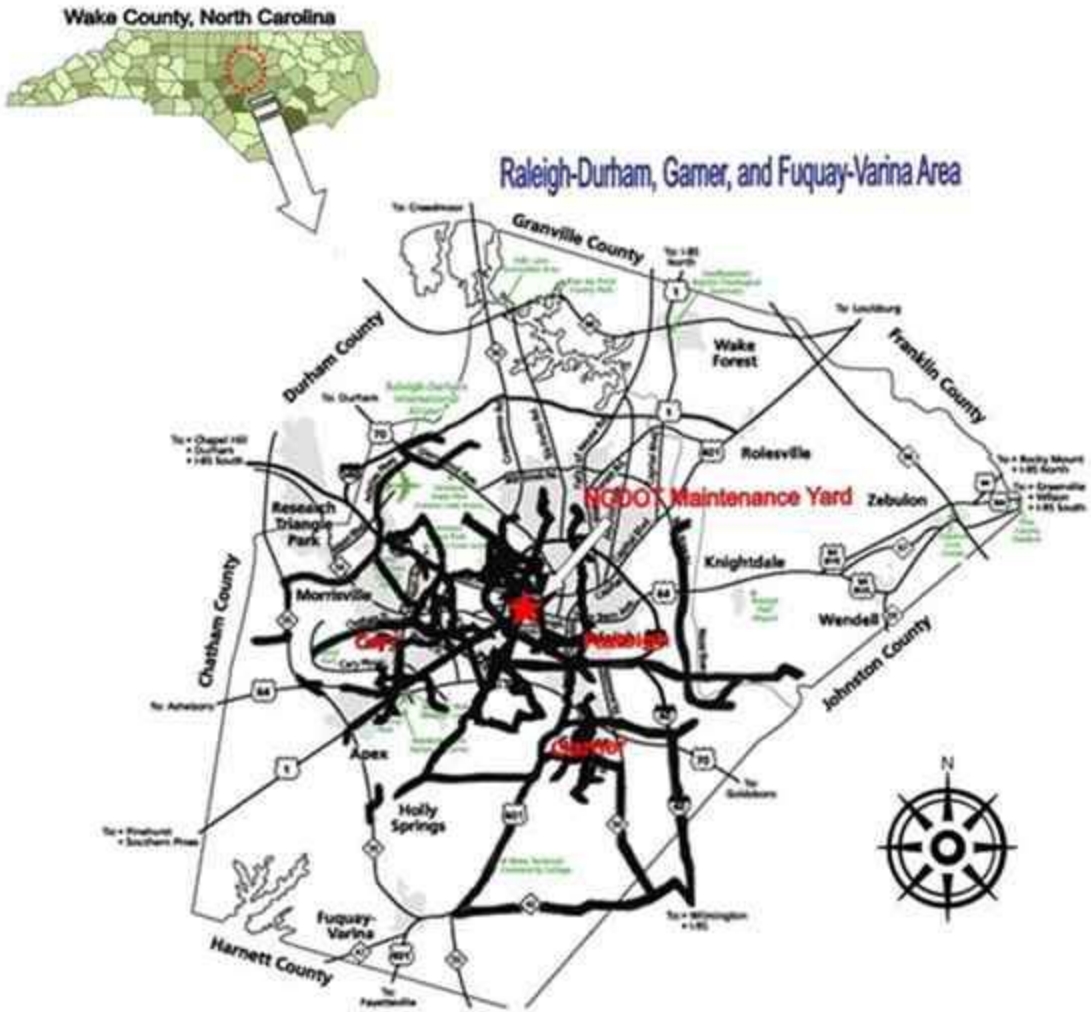
Study Region: Wake County, North Carolina



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Overall Average Comparisons: Average Percent Difference, B20 vs. Petroleum Diesel

	Unloaded	Loaded	Combined	Engine Dyno.
Fuel	7	7	7	NR
NO	-11 (-9)[a]	-12 (-12)[a]	-11 (-10)[a]	2
HC	-21	-20	-21	-21
CO	-11	-12	-11	-11
CO_2	4	3	3	NR
PM	-8	-12	-10	-10

[a] *Applied NO_X humidity Correction Factor for diesel engines based on EPA 40 CFR*

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Field Measurement of 8 Cement Mixers: B20 vs. Petroleum Diesel

	Average Percent Change for B20 vs. PD
Fuel Use	0.5
CO_2	0.5
NO	-2
PM	-20
HC	-28.5
CO	-20.5

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Procedure for PEMS Installation and Field Measurement of NONROAD Vehicles

STEP 1

Pre-Installation

Sensor Unit

External Battery

Main Unit Safety Cage

STEP 2

Installation

Gas & PM Samplers

Vehicle Activity Monitors

System Warm-up

STEP 3

Data Collection

Periodic System Check

Laptop-Activity Recording

Video-Activity Recording

Bottom Line: Petroleum Diesel to B20 Biodiesel for Nonroad Construction Vehicles

Percent Changes in Fuel-Based Average Emission Rate after Switching Fuel from Petroleum Diesel to B20 Biodiesel

Vehicle	NO [a]	PM	HC	CO
Backhoe (5)	-4.1	-17	-27	-17
Front-end Loader (4)	-1.0	-19	-35	-42
Motor Grader (6)	-0.16	-18	-17	-17
Overall (15)	-1.8	-18	-26	-25

[a] NO emissions were corrected based on ambient temperature and humidity

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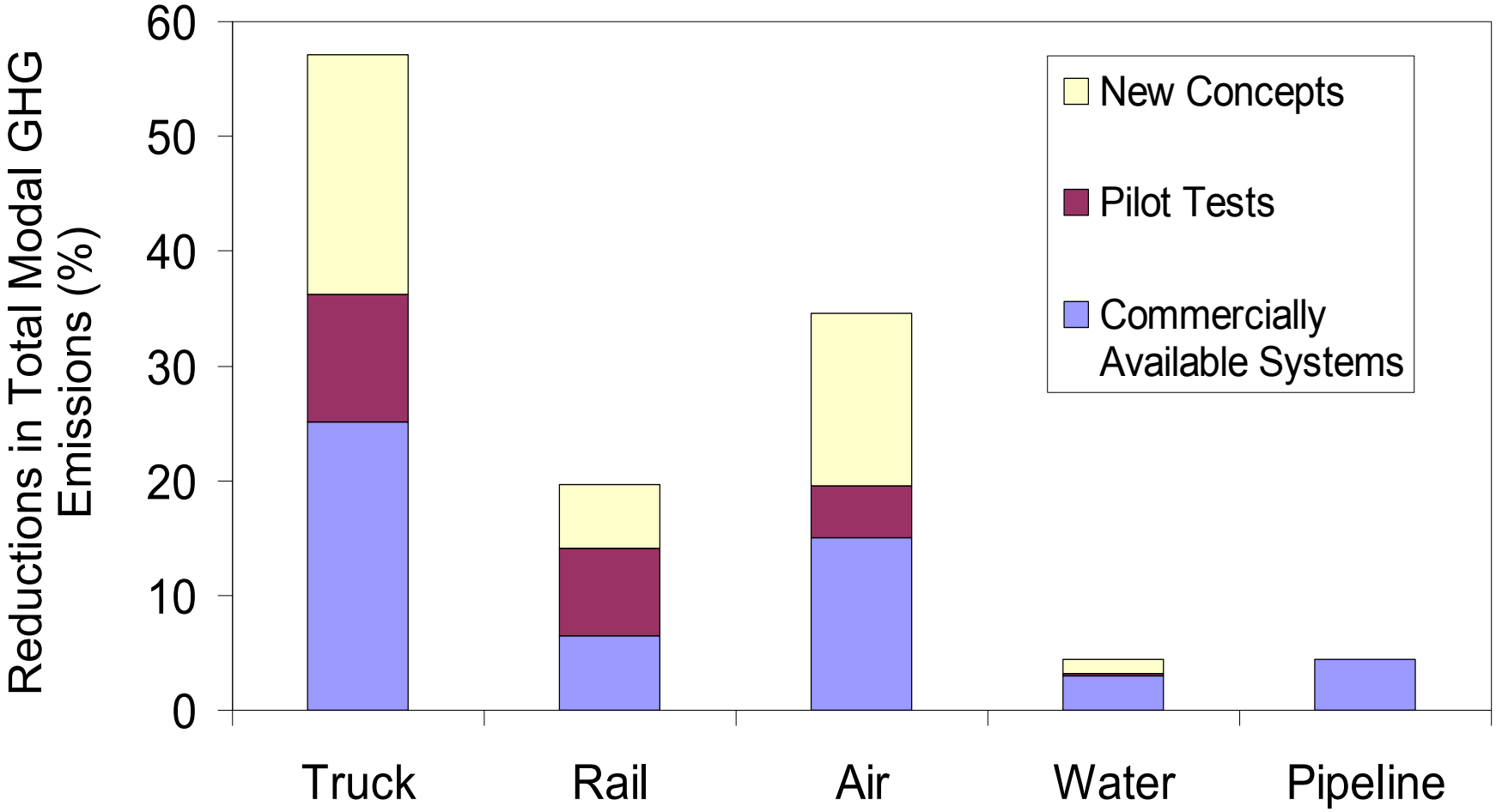
Total 2025 Modal GHG Emissions Reductions Compared to 2025 Without Best Practices



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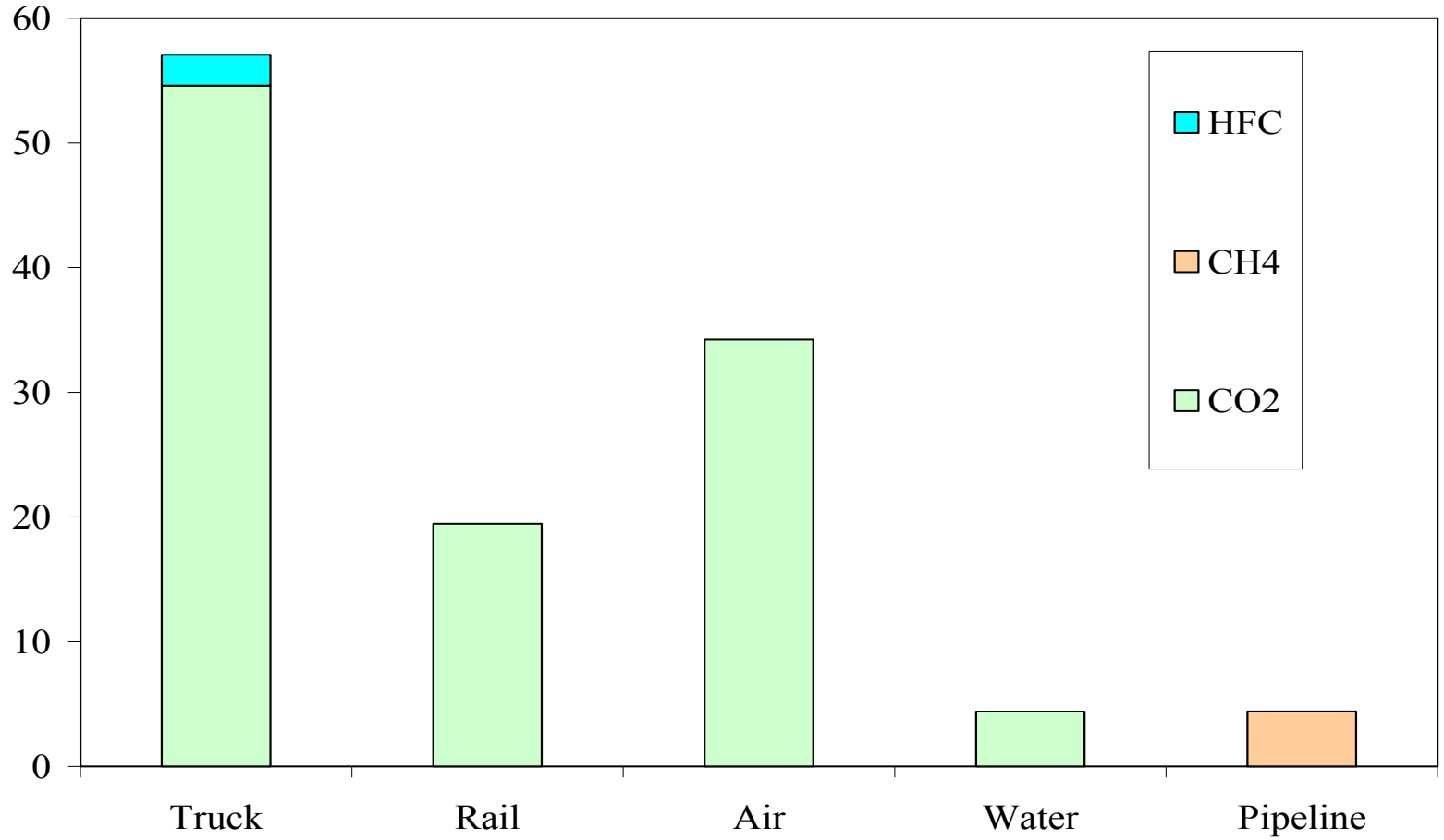

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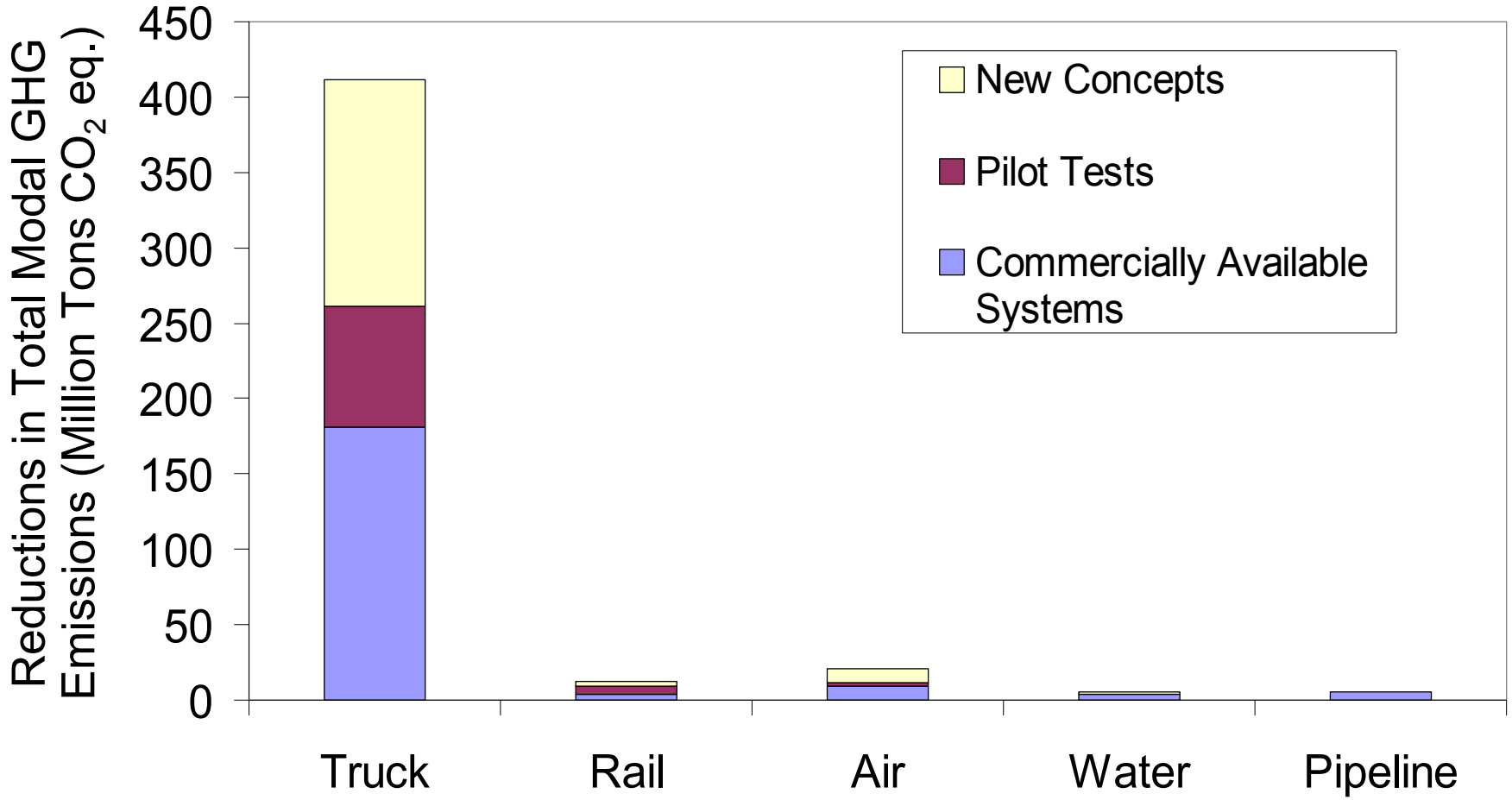
Total 2025 Modal GHG Emissions Reductions Compared to 2025 Without Best Practices



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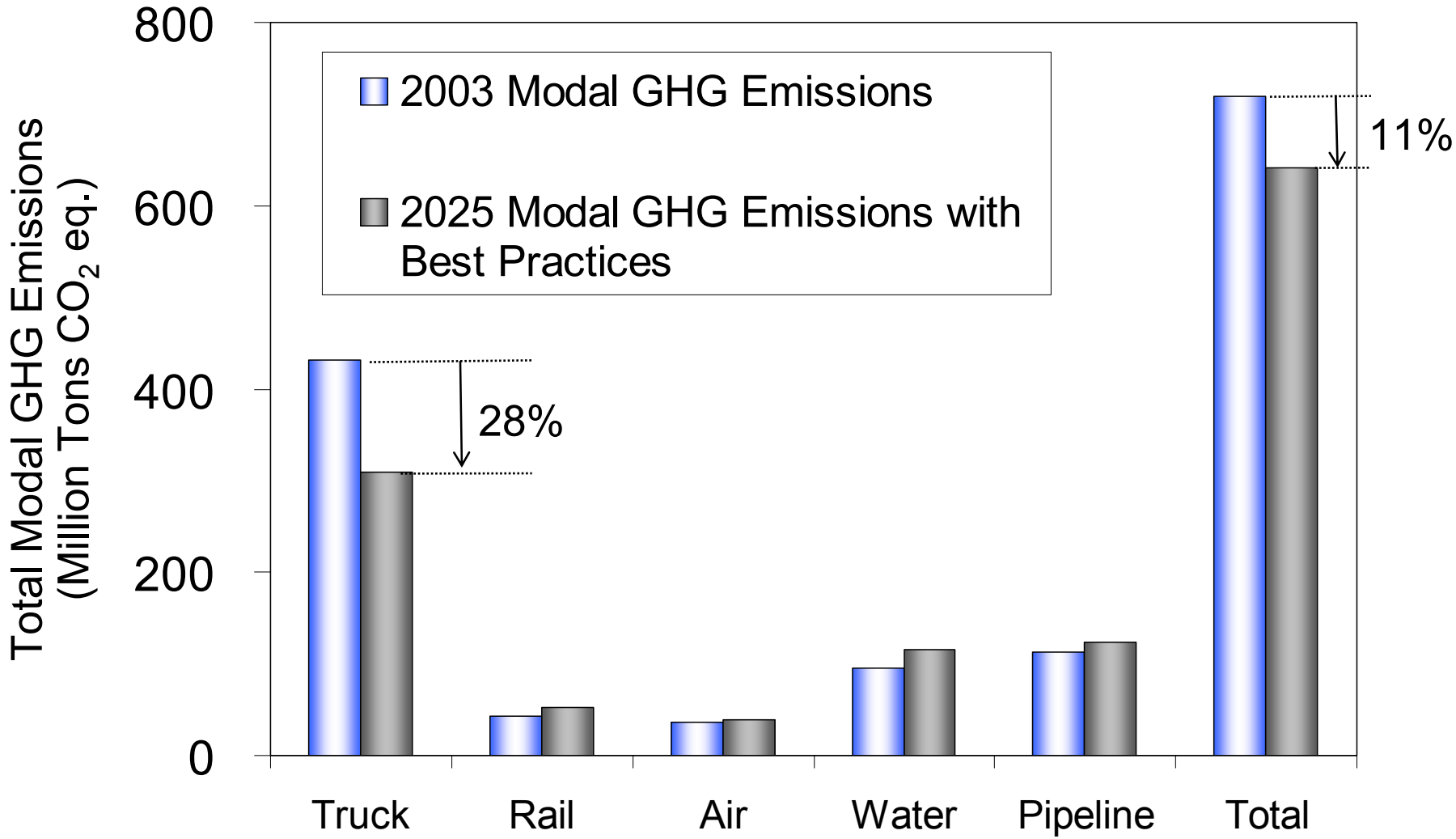
Changes in GHG Emissions from 2003 to 2025 with Best Practices

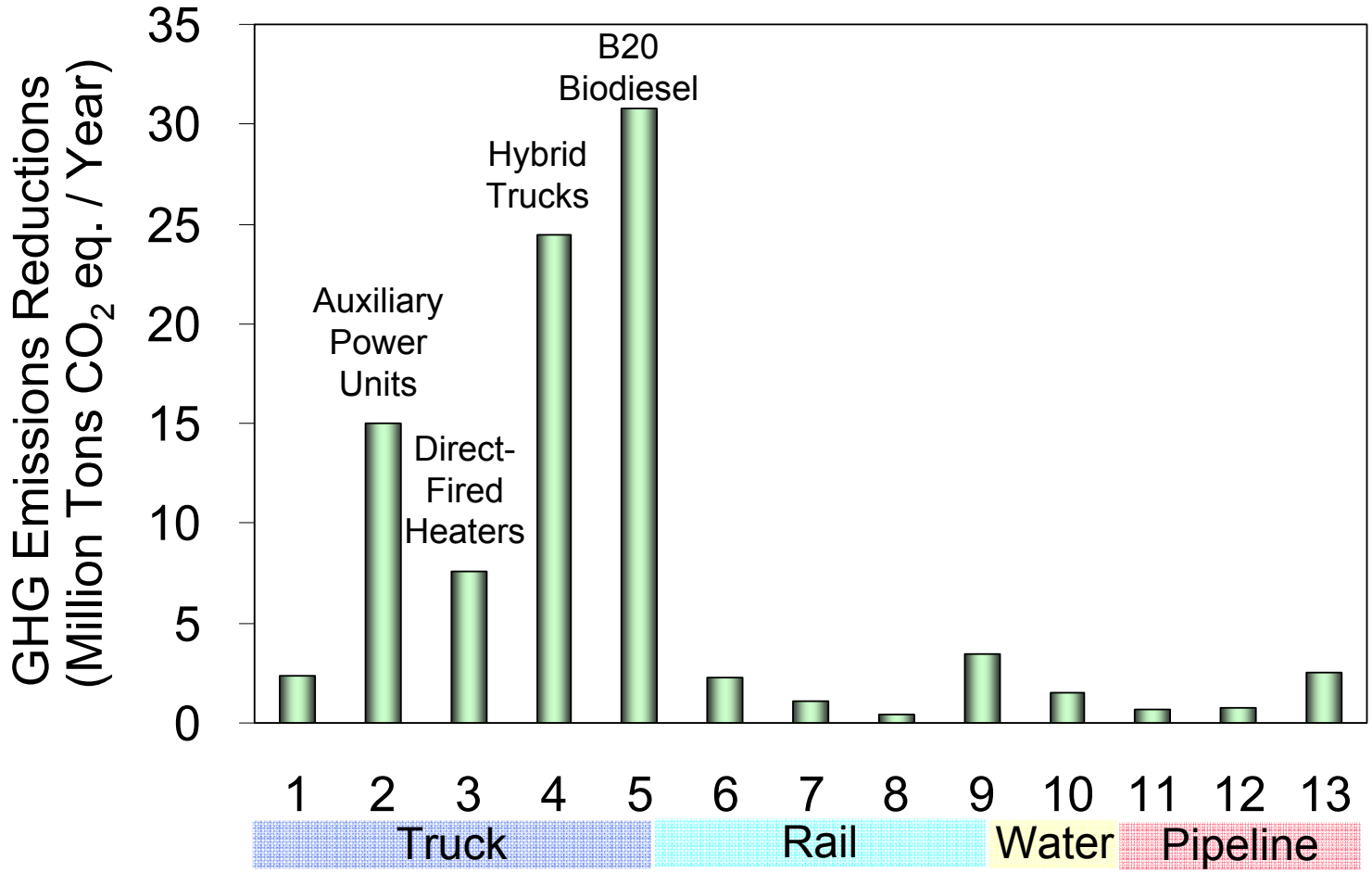


Comparison of Best Practices Whose Costs Are Assessed Quantitatively

- To date, sufficient information has been obtained to assess the costs of 13 practices quantitatively.

Mode	Name of Best Practices
Truck	1. Off-board truck stop electrification; 2. Auxiliary power units; 3. Direct-fired heaters; 4. Hybrid trucks; 5. B20 biodiesel
Rail	6. Combined diesel powered heating and start/stop system; 7. Battery-diesel hybrid switching locomotive; 8. Plug-in units; 9. B20 biodiesel
Water	10. B20 biodiesel
Pipeline	11. Natural gas-powered pipeline process control device replaced by compressed air-powered devices; 12. Natural gas-powered pipeline process control device replaced by low-bleed pneumatic devices; 13. “Hot Tap” method

Comparison of Best Practices Whose Costs Are Assessed Quantitatively (Continued)



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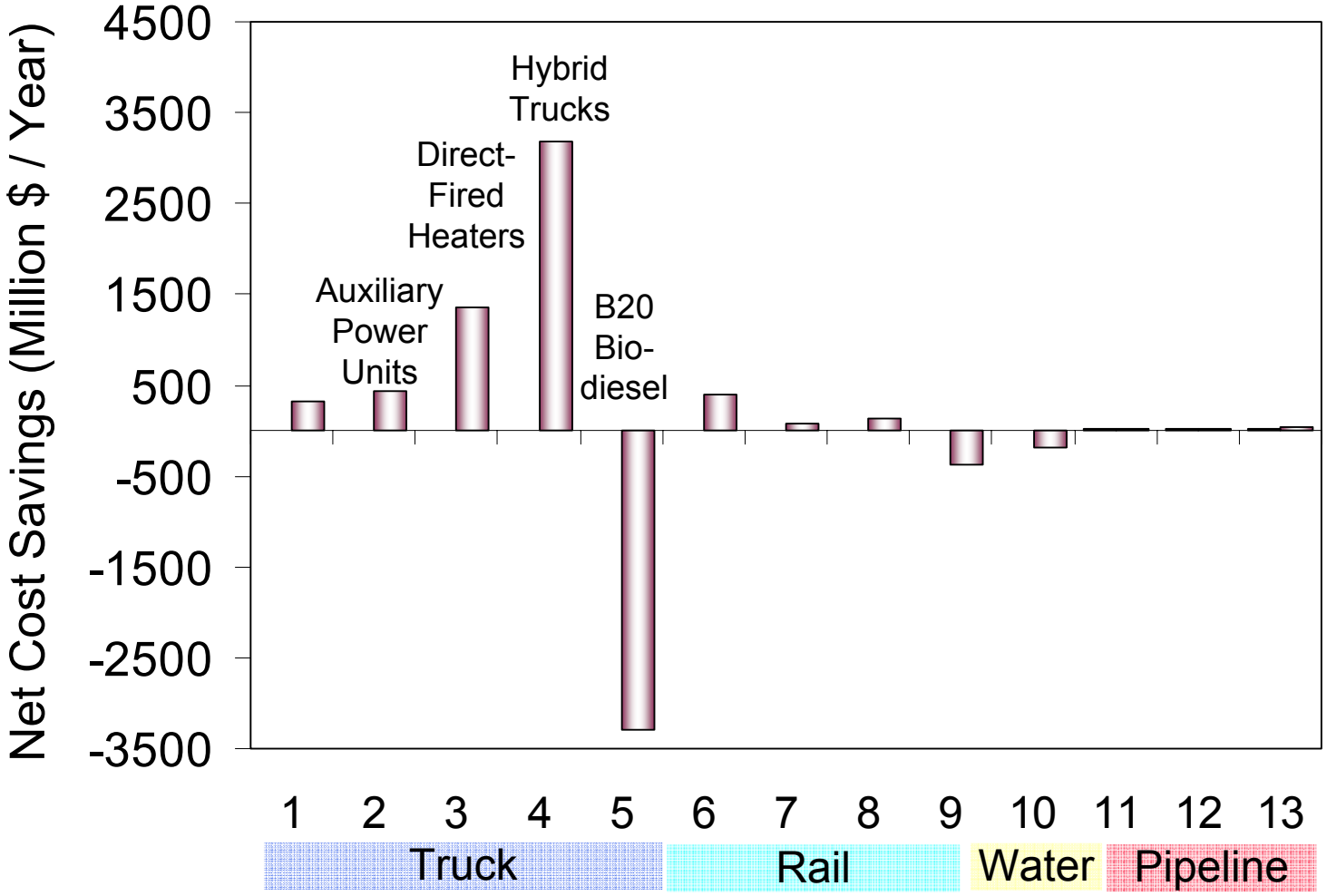
Comparison of Best Practices Whose Costs Are Assessed Quantitatively (Continued)



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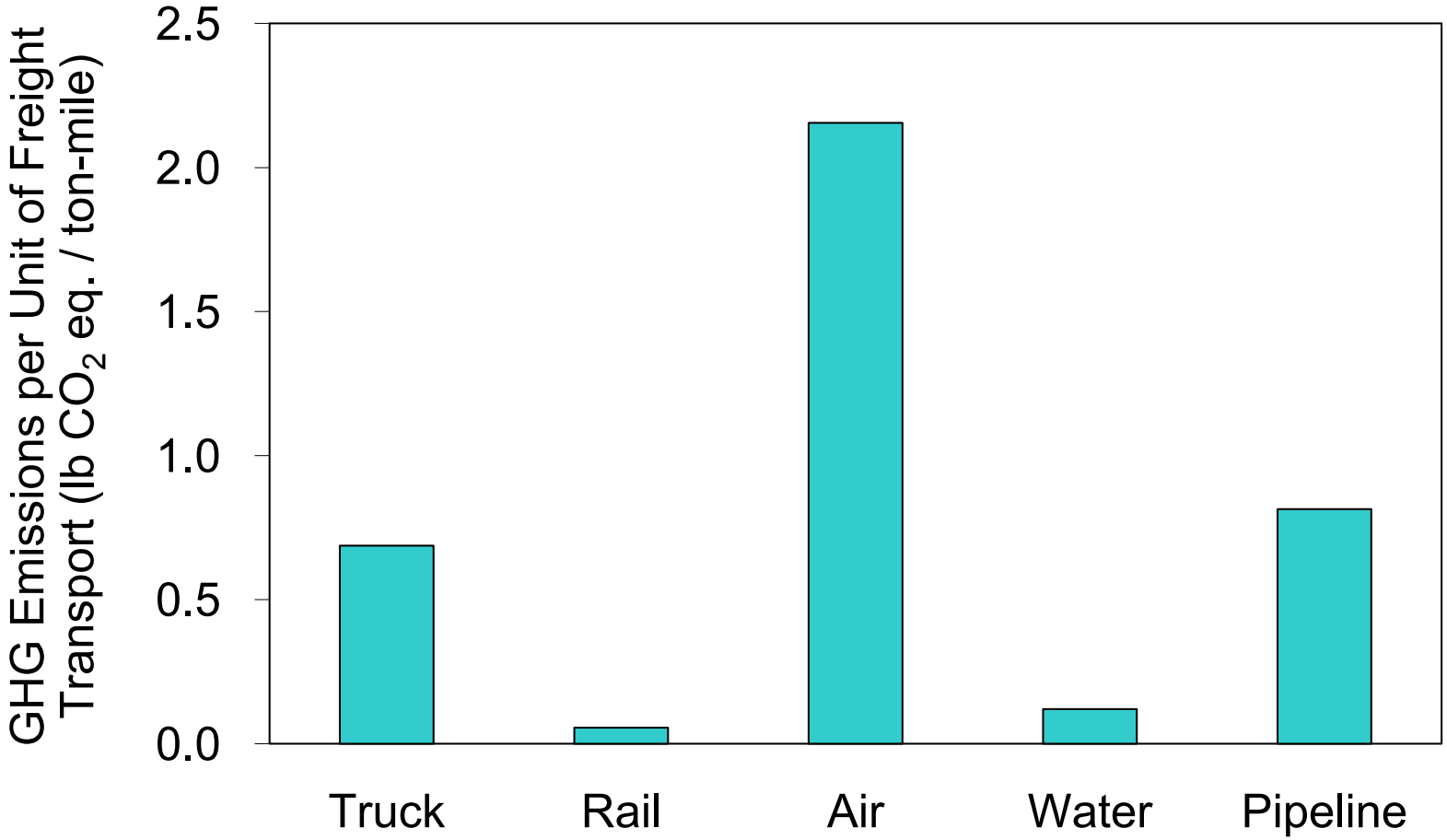
Inter-Modal Comparison of Average Modal GHG Emission Rates



For example, GHG emissions reductions of 85% are possible if long-haul truck transport is replaced with a combination of rail and truck transport. Actual reductions will depend on site-specific logistics.

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Overview of the Organization and Content of Guidebook (www4.ncsu.edu/~frey/)

Background and Methodology

- Definitions and Concepts **Chapter 2**
- Methodology **Chapter 3**
- Fuel Properties **Appendix F**

Assessments of Individual and Subgroups of Best Practices by Mode

Mode	Summary Material	Supporting Details
Truck	**Chapter 4**	**Appendix A**
Rail	**Chapter 5**	**Appendix B**
Air	**Chapter 6**	**Appendix C**
Water	**Chapter 7**	**Appendix D**
Pipeline	**Chapter 8**	**Appendix E**

- Summaries of and Comparisons Between Modes **Chapter 9**
- Conclusions and Recommendations **Chapter 10**

Conclusions

- Aggressive implementation of best practices may lead to a *net decrease* in total GHG emissions in freight transportation
- Even larger percentage reductions are possible if inter-modal shifts (e.g., substitute rail for truck) are encourage

Conclusions (Continued)

- There is limited quantitative cost data upon which to base assessments of the costs of best practices
- For 13 best practices for which adequate cost data are available:
  - The normalized cost savings per unit of GHG emissions reduction was highly variable
  - The variability mostly depends on the magnitudes of their energy cost savings

Conclusions (Continued)

- Some best practices (e.g., biodiesel for trucks) offer potential for large magnitudes in GHG emissions reductions, but may not be as cost-effective
  - From a national policy perspective, governments should promote research, development, and demonstration (RD&D) to foster best practices that lead to large absolute reductions in GHG emissions
- Some best practices may lead to “no regrets”
  - e.g., net cost savings to an operator
  - Additional benefits of GHG emissions or energy use reduction

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Ongoing Work

- Further analysis and comparison of B20 vs. Petroleum Diesel emissions data for in-use measurements of 35 diesel engines
- Measurement and modeling of plug-in hybrid electric school bus
- Plans to test two passenger locomotives with ULSD and soy-based B20
- Completion of field study of idling activity, APU usage, fuel use, and emissions for 20 long-haul trucks
- Effect of alternative fuel, vehicle technology, and land-use on mobile source emissions
- Methods for “micro-scale” modeling of vehicle activity, fuel use, and emissions
- Linkages between highway emissions and near-roadway air quality, exposure, and health risk
- Modeling and evaluation of gasification-based systems
- International collaborations: Portugal, China

Recommendations

- Update GHG potential best practice information as new information becomes available
- Revise or develop cost estimates as new data become available
- Evaluate key assumptions (e.g., market penetration rates) that influence the selection of best practices via sensitivity analysis
- Develop tools (e.g., a decision tree, a decision support framework) to support decision making regarding best practices

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