

# Biodiesel and Renewable Diesel Research Study

December 2010  
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California Environmental Protection Agency



**Air Resources Board**

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## Biodiesel/Renewable Diesel Study

### Biodiesel/Biofuels Characterization Study

- Soy-based and animal-based biodiesel, renewable diesel (Neste Oil), and GTL
- Blend levels B0, B5, B20, B50, B100 --- R20, R50, R100
- Engine Dyno Testing at CE-CERT
  - 2 engines - 2006 Cummins ISM + 2007 DDC MBE4000
  - Test cycles (FTP, Light UDDS, CARB HHDDT 40 & 50 mph cruise)
  - 3 different power levels to look at biodiesel impacts vs. load
  - Regulated emissions
  - NO<sub>x</sub> mitigation studies
- CARB chassis dynamometer facility in Los Angeles
  - 4 vehicles (2000 Cat C-15, 2007 MBE4000 with DPF, 2006 Cummins ISM, 2010 Cummins ISX with DPF and SCR)
  - Test cycles: UDDS and CARB HHDDT 50 mph cruise
  - Characterization of PM and VOCs by CARBs MLD division
    - VOCs, N<sub>2</sub>O, carbonyls, EC/OC, ions, elements (Cat C-15 & MBE4000)
    - VOCs & carbonyls on Cummins ISM
  - Toxicity testing with UC Davis
    - PAHs/nitro PAHs, reactive carbonyls, mutagenicity with TA98&100, human lung/macrophage assay, and Comet assay
    - 2000 Cat C-15 and the 2007 MBE4000 (soy only)

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## Biodiesel/Renewable Diesel Study

### Biodiesel/Biofuels Characterization Study Off-Road Engines

- CARB's Stockton facility
  - John Deere PE 4045HF285 Diesel Engine
  - ISO 8178 - 8 mode steady state test
  - Soy-based (B20, B50, B100) and animal-based (B5, B20, B100)
- Transportation refrigeration units (TRUs)
  - 1998 pre-Tier 1 37.8 hp engine
  - ISO 8178 - 8 mode steady state test
  - CARB, soy-based B5, B20, B50, and B100
  - Regulated emissions and N<sub>2</sub>O
- Durability Evaluation

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## On-Road Engine Test Matrix

- 2006 Cummins
  - Soy and Animal-based biodiesel, Renewable and GTL diesel
    - UDDS, FTP, 40 mph & 50 mph Cruise
  - Extensive Mitigation testing with additives and renewable blends over FTP
- 2007 MBE4000
  - Equipped with OEM DPF
  - Soy and Animal-based biodiesel
    - UDDS, FTP, 50 mph Cruise
  - Limited mitigation testing with additives and renewable blends over FTP

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## Fuel Properties

	CARB ULSD	NExBTL Renewable Diesel	GTL	Soy- biodiesel	Animal- biodiesel
API gravity (@ 60°F)	39.3	51.3	48.4	28.5	28.5
Aromatics, vol. %	18.7	0.4	0.5	NA	NA
PNAs, wt. %	1.5	0.1	<0.27	NA	NA
Cetane number, D613	55.8	72.3	>74.8	47.7	57.9
Cetane number, IQT	NA	74.7	NA	NA	NA
Sulfur, ppm	4.7	0.3	0.9	0.7	2

Notes: NA = either Not Available or Applicable; IQT = ignition quality test derived cetane number

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## Engine 1 – 2006 Cummins ISM Test Runs

- Biodiesel Results show trends consistent with expectations
  - Increasing NO<sub>x</sub> for the biodiesel blends
  - Decreasing PM for the biodiesel blends
  - Decreasing THC for the biodiesel blends
  - Decreasing CO for the Animal, but not the Soy
  - Increasing fuel consumption for biodiesel blends
- Renewable diesel showed reductions in both NO<sub>x</sub> & PM
- CO<sub>2</sub> increased slightly for higher biodiesel blends
- Complications with 50 mph Cruise due to different engine operating modes

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## Engine 2 – 2007 MBE4000 Test Runs

- Biodiesel Results show trends consistent with expectations
  - Increasing NO<sub>x</sub> for the biodiesel blends
  - PM, CO, and THC showed limited trends with fuel due to DPF
  - Increasing fuel consumption for biodiesel blends
- CO<sub>2</sub> increased slightly for higher biodiesel blends
- Emissions sampled between forced regenerations
  - Eliminate complexity of separating fuel and regeneration effects
  - Forced regenerations were performed regularly

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## Soy Feedstock Test Matrix

A = Light UDDS B = FTP C1 = ARB 40 mph Cruise C = ARB 50 mph Cruise  
Engine 1-2006 cummins ISM

Soy based biodiesel

Day	Fuel	Cycle	Day	Fuel	Cycle	Day	Fuel	Cycle	Day	Fuel	Cycle	Day	Fuel	Cycle	Day	Fuel	Cycle																								
1	CARB	A	2	B20	A	3	B50	A	4	CARB	A	5	B100	A	6	B20	A	7	CARB	A	8	B50	A	9	B100	A	10	CARB	A	11	B20	A	12	B50	A	13	B100	A	14	CARB	A
1	C1	B	2	B20	B	3	B50	B	4	CARB	B	5	B100	B	6	B20	B	7	CARB	B	8	B50	B	9	B100	B	10	CARB	B	11	B20	B	12	B50	B	13	B100	B	14	CARB	B
1	B	C1	2	B20	C1	3	B50	C1	4	CARB	C1	5	B100	C1	6	B20	C1	7	CARB	C1	8	B50	C1	9	B100	C1	10	CARB	C1	11	B20	C1	12	B50	C1	13	B100	C1	14	CARB	C1
1	A	B	2	B20	B	3	B50	B	4	CARB	B	5	B100	B	6	B20	B	7	CARB	B	8	B50	B	9	B100	B	10	CARB	B	11	B20	B	12	B50	B	13	B100	B	14	CARB	B
1	A	C1	2	B20	C1	3	B50	C1	4	CARB	C1	5	B100	C1	6	B20	C1	7	CARB	C1	8	B50	C1	9	B100	C1	10	CARB	C1	11	B20	C1	12	B50	C1	13	B100	C1	14	CARB	C1
1	A	A	2	B20	A	3	B50	A	4	CARB	A	5	B100	A	6	B20	A	7	CARB	A	8	B50	A	9	B100	A	10	CARB	A	11	B20	A	12	B50	A	13	B100	A	14	CARB	A
1	A	A	2	B20	A	3	B50	A	4	CARB	A	5	B100	A	6	B20	A	7	CARB	A	8	B50	A	9	B100	A	10	CARB	A	11	B20	A	12	B50	A	13	B100	A	14	CARB	A
1	A	A	2	B20	A	3	B50	A	4	CARB	A	5	B100	A	6	B20	A	7	CARB	A	8	B50	A	9	B100	A	10	CARB	A	11	B20	A	12	B50	A	13	B100	A	14	CARB	A
1	A	A	2	B20	A	3	B50	A	4	CARB	A	5	B100	A	6	B20	A	7	CARB	A	8	B50	A	9	B100	A	10	CARB	A	11	B20	A	12	B50	A	13	B100	A	14	CARB	A

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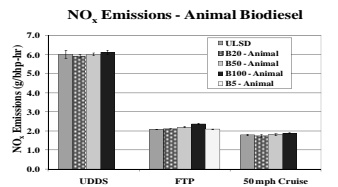
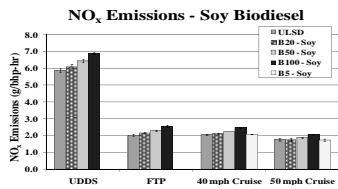
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## NO<sub>x</sub> Results 2006 Cummins




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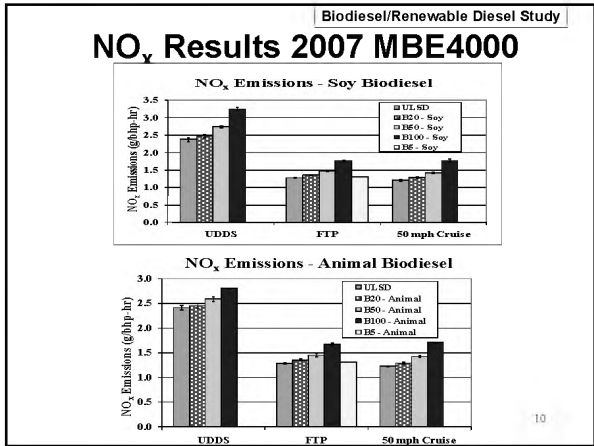
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**Biodiesel/Renewable Diesel Study**

## Biodiesel NO<sub>x</sub> Emissions Engines 1 & 2

	CARB vs.	2006 Cummins-ISM				2007 MBE4000			
		Soy-based		Animal-based		Soy-based		Animal-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	4.1%	0.062	-1.5%	0.376	4.4%	0.005	1.6%	0.000
	B50	9.8%	0.000	0.1%	0.935	15.3%	0.000	7.3%	0.000
	B100	17.4%	0.000	1.9%	0.213	36.8%	0.000	16.8%	0.000
FTP	B5	2.3% (Min)	0.000	0.3%	0.298	0.9%	0.007	1.3%	0.000
	B10	2.6% (Min)	0.000						
	B20	6.6%	0.000	1.5%	0.000	5.9%	0.000	5.0%	0.000
40 mph Cruise	B50	13.2%	0.000	6.4%	0.000	15.3%	0.000	12.1%	0.000
	B100	26.6%	0.000	14.1%	0.000	38.1%	0.000	29%	0.000
	B5	1.7%	0.135						
50 mph Cruise	B20	3.9%	0.000						
	B50	9.1%	0.000						
	B100	20.9%	0.000						
2007 MBE4000	B5	-1.1%	0.588						
	B20	0.3%	0.800	-2.3%	0.151	8.9%	0.000	5.9%	0.000
	B50	6.3%	0.001	0.8%	0.588	18.2%	0.000	16.9%	0.000
	B100	18.3%	0.000	5.3%	0.000	47.1%	0.000	39.4%	0.000

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- Biodiesel/Renewable Diesel Study**
- ## NO<sub>x</sub> Characterization Summary
- NO<sub>x</sub> increased with biodiesel for nearly test combinations
  - NO<sub>x</sub> increases larger than "average" EPA values
  - NO<sub>x</sub> increases larger for newer 2007 MBE4000 vs. 2006 Cummins
  - NO<sub>x</sub> increases as a function of load differed between engines
    - Highest NO<sub>x</sub> impact for FTP for 2006 Cummins (complications with 50 mph cruise)
    - NO<sub>x</sub> impacts for 2007 MBE4000 increased with increasing load
  - Successful NO<sub>x</sub> mitigation strategies included DTBP and renewable/GTL blends
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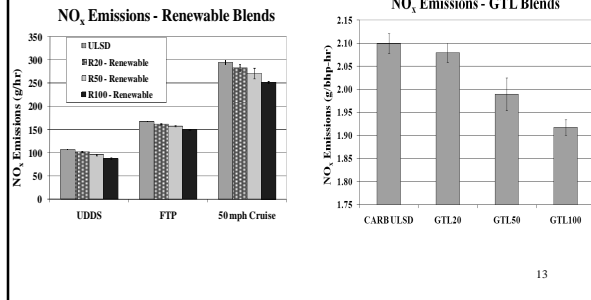
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## NO<sub>x</sub> Results 2006 Cummins



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## Renewable/GTL NO<sub>x</sub> Emissions 2006 Cummins

	CARB vs.	Renewable		GTL	
		Difference %	P-values	Difference %	P-values
UDDS	20% blend	-4.9%	0.000		
	50% blend	-10.2%	0.000		
	100% blend	-18.1%	0.000		
FTP	20% blend	-2.9%	0.000	-0.9%	0.053
	50% blend	-5.4%	0.000	-5.2%	0.000
	100% blend	-9.9%	0.000	-8.7%	0.000
50 mph Cruise	20% blend	-3.8%	0.007		
	50% blend	-7.8%	0.000		
	100% blend	-14.2%	0.000		

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## Strategies for NO<sub>x</sub> Mitigation

- Additives
- Renewable/biodiesel blends
- GTL/biodiesel blends
- Additional testing to certify alternative formulations in planning stages

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## Additive Testing

- 2- ethyl-hexyl-nitrate (EHN)
  - 1% level in B5, B10, and B20
- Di-tert-butyl-peroxide (DTBP)
  - 1% level in B10 and B20
- Both additives have been studied by NREL and SwRI
- Use B20-soy with highest NO<sub>x</sub> disbenefit
- All testing on FTP
- DTBP successful at 1% level with B20
- 2-EHN unsuccessful even at 1% level with B5

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## Renewable/GTL Mitigation Blends

- Higher Renewable Blends Successful (Engine 1)
  - R80/B20, R55/CARB25/B20
- Several blends w/ ~B5/B10 successful (Engine 1)
  - CARB70/R20/B5-S, CARB80/R15orG15/B5-S,
  - CARB80/R13/B3S/B4A,CARB80/R10/B10-S+0.25DTBP
- Some blends w/B10/B20 unsuccessful (Engine 1)
  - CARB70/R20/B10-S
  - CARB80/G10/B10-S, CARB53/G27/B20-S
- Engine 2
  - B5-S + 0.25% DTBP successful
  - CARB80/R15/B5-S unsuccessful

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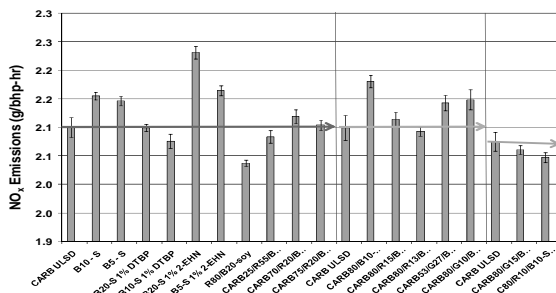
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## NO<sub>x</sub> Mitigation 2006 Cummins ISM




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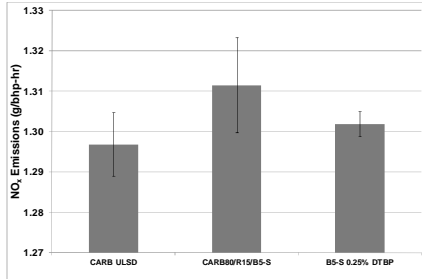
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## NO<sub>x</sub> Mitigation 2007 MBE4000



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## NO<sub>x</sub> Mitigation Results

CARB vs.	2006 Cummins ISM		2007 MBE4000	
	% Difference	P-values	% Difference	P-values
B5 - S	2.2%	0.000		
B10 - S	2.6%	0.000		
B20 - S*	6.6%	0.000		
B20-S 1% DTBP	0.0%	0.959		
B10-S 1% DTBP	-1.1%	0.002		
B20-S 1% 2-EHN	6.3%	0.000		
B5-S 1% 2-EHN	3.1%	0.000		
R80/B20-soy	-3.0%	0.000		
CARB25R55/B20-S	-0.8%	0.029		
CARB70R20/B10-S	0.9%	0.014		
CARB75R20/B5-S	0.2%	0.674		
CARB80/B10-S/B10-A	3.9%	0.000		
CARB80R15/B5-S	0.7%	0.117	1.1%	0.029
CARB80R13/B5-S/B4-A	-0.3%	0.501		
CARB53G27/B20-S	2.1%	0.000		
CARB80G10/B10-S	2.4%	0.000		
CARB80G15/B5-S	-0.7%	0.068		
CARB80R10/B10-S 0.25% DTBP	-1.3%	0.002		
B5-S 0.25% DTBP			0.4%	0.175

\* From testing with soy-biodiesel feedstock

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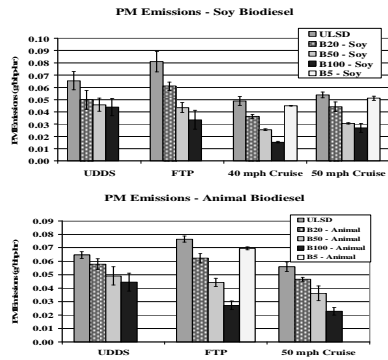
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## PM Results 2006 Cummins



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### Biodiesel Durability Evaluation

- Literature review and user survey
- Biodiesel fleet user survey
  - 40 agencies – national parks, county & municipal fleets, schools, state DOTs, transit agencies, companies, US postal service
  - Storage & handling, performance, operability, biodiesel type and level
- Literature Review
  - Biodiesel production has significantly expanded
  - Fuel Quality
    - ASTM D6751 for B100 and ASTM D7467 for B6 to B20
    - Some differences in stability requirements compared to Europe
    - BQ9000 - Some issues with smaller production volume facilities
  - Fuel storage and stability
    - Oxidation stability and solvent properties
  - Materials compatibility and engine durability
    - Elastomer degradation, lubricity, oil dilution
  - Vehicle performance
    - Energy content, most users did not observe noticeable impact
  - Cold weather issues
    - Higher cold point and pour point, winter blends to -14°F

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### PM Test Results

	CARB vs.	2006 Cummins ISM				2007 MBE4000			
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	-24%	0.002	-10%	0.009	-94%	0.187	224%	0.779
	B50	-30%	0.000	-24%	0.001	9%	0.874	285%	0.219
	B100	-33%	0.000	-31%	0.000	-37%	0.470	1043%	0.000
FTP	B5	-6% (Mit)	0.000	-9%	0.000	-61%	0.096	-32%	0.553
	B10	-17% (Mit)	0.000	0.000	0.000				
	B20	-25%	0.000	-19%	0.000	-4%	0.944	40%	0.341
40 mph Cruise	B50	-46%	0.000	-42%	0.000	58%	0.216	15%	0.757
	B100	-58%	0.000	-64%	0.000	64%	0.403	-24%	0.611
	B5	-6%	0.101						
50 mph Cruise	B20	-26%	0.000						
	B50	-48%	0.000						
	B100	-69%	0.000						
50 mph Cruise	B5	-5%	0.036						
	B20	-18%	0.000	-16%	0.000	-19%	0.746	-49%	0.143
	B50	-43%	0.000	-35%	0.000	2%	0.970	-58%	0.103
	B100	-50%	0.000	-59%	0.000	-100%	0.704	-39%	0.237

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### THC Test Results

	CARB vs.	2006 Cummins ISM				2007 MBE4000			
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	-12%	0.000	-16%	0.000	-11%	0.770	33%	0.000
	B50	-28%	0.000	-38%	0.000	27%	0.400	8%	0.695
	B100	-55%	0.000	-73%	0.000	-18%	0.663	6%	0.755
FTP	B5	-1% (Mit)	0.136	-3%	0.011	38%	0.005	13%	0.612
	B10	-6% (Mit)	0.000						
	B20	-11%	0.000	-13%	0.000	33%	0.005	13%	0.376
40 mph Cruise	B50	-29%	0.000	-36%	0.000	25%	0.018	-13%	0.568
	B100	-63%	0.000	-71%	0.000	20%	0.081	5%	0.756
	B5	-1%	0.573						
50 mph Cruise	B20	-16%	0.000						
	B50	-36%	0.000						
	B100	-70%	0.000						
50 mph Cruise	B5	-2%	0.222						
	B20	-12%	0.000	-14%	0.000	-5%	0.801	17%	0.425
	B50	-31%	0.000	-37%	0.000	-20%	0.430	-13%	0.448
	B100	-68%	0.000	-73%	0.000	-13%	0.594	3%	0.905

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## CO Test Results

	CARB vs.	2006 Cummins ISM				2007 MBH4000					
		% Difference	Soy-based		Animal-based		% Difference	Soy-based		Animal-based	
			P-values	% Difference	P-values	% Difference		P-values	% Difference	P-values	
UDDS	B20	5%	0.115	-10%	0.000	-52%	0.453	18%	0.903		
	B50	26%	0.000	-12%	0.000	-111%	0.154	-16%	0.875		
	B100	62%	0.000	-20%	0.000	-67%	0.491	109%	0.238		
FTP	B5	-1% (MI)	0.405	-4%	0.008	-20%	0.135	-11%	0.202		
	B10	-2% (MI)	0.151								
	B20	-3%	0.078	-7%	0.000	13%	0.534	-3%	0.841		
40 mph Cruise	B50	-4%	0.038	-14%	0.000	-50%	0.031	-39%	0.040		
	B100	3%	0.163	-27%	0.000	-74%	0.002	-73%	0.000		
	B5	2%	0.427								
50 mph Cruise	B20	-3%	0.160								
	B50	0%	0.986								
	B100	0%	0.868								
50 mph Cruise	B5	1%	0.649								
	B20	-2%	0.330	-7%	0.003	-6%	0.809	-7%	0.733		
	B50	-6%	0.002	-9%	0.066	-33%	0.302	-36%	0.144		
	B100	-14%	0.000	-25%	0.000	-21%	0.508	-55%	0.027		