# Biodiesel and Renewable Diesel Research Study

**September 24, 2009**
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**California Environmental Protection Agency**

**Air Resources Board**





## Testing/Reporting Status

- Testing on both engines is completed
- Data for Engines #1 & #2 on website
- Draft Memorandums –
  - Engine #1 on website
  - Engine #2 ready for CARB review by mid-October

# Engine Parameters

- 2006 Cummins ISM 370 – Engine 1
  - In-line, 6 cylinder, 4-stroke, 10.8 L engine
  - 370 hp / 1450 ft-lbs @ 1800 rpm
  - Turbo charged with EGR
- 2007 MBE4000 – Engine 2
  - Equipped with OEM DPF
  - In-line, 6 cylinder, 4-stroke, 12.8 L engine
  - 410 hp @ 1900 rpm
  - Turbo charged with EGR





# Test Matrix

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

# Engine 1 – 2006 Cummins Test Runs

- Biodiesel Results show trends consistent with expectations
  - Increasing $NO_x$ 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 $NO_x$ & PM
- $CO_2$ increased slightly for higher biodiesel blends
- Complications with 50 mph Cruise due to different engine operating modes





# Engine 2 – 2007 MBE4000 Test Runs

- Biodiesel Results show trends consistent with expectations
  - Increasing $NO_x$ for the biodiesel blends
  - PM, CO, and THC showed limited trends with fuel due to DPF
  - Increasing fuel consumption for biodiesel blends
- $CO_2$ increased slightly for higher biodiesel blends
- emissions sampled between forced regenerations
  - Eliminate complexity of separating fuel and regeneration effects
  - Forced regenerations were performed regularly
  - Additional studies of regeneration effects may be conducted in the future

# Soy Feedstock Test Matrix

A = Lght. UDDS B = FTP C1 = ARB 40 mph Cruise C = ARB 50 mph Cruise

**Engine 1-2006 cummins ISM**

***Soy based biodiesel***

| Day 1 | | Day 2 | | Day 3 | | Day 4 | | Day 5 | | Day 6 | | Day 7 | | Day 8 | | Day 9 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Cycle | Fuel | Cycle | Fuel | Cycle | Fuel | Cycle | Fuel | Cycle | Fuel | Cycle | Fuel | Cycle | Fuel | Cycle | Fuel | Cycle |
| CARB | A | B20 | B | B50 | A | CARB | C1 | B100 | B | B20 | C1 | CARB | B | B50 | A | B100 | A |
| | C1 | | A | | B | | A | | C1 | | B | | A | | B | | C1 |
| | B | | C1 | | C1 | | B | | A | | A | | C1 | | C1 | | B |
| B20 | C1 | B50 | B | CARB | C1 | B100 | A | B20 | B | CARB | A | B50 | B | B100 | C1 | CARB | B |
| | B | | C1 | | A | | B | | A | | C1 | | A | | A | | C1 |
| | A | | A | | B | | C1 | | C1 | | B | | C1 | | B | | A |

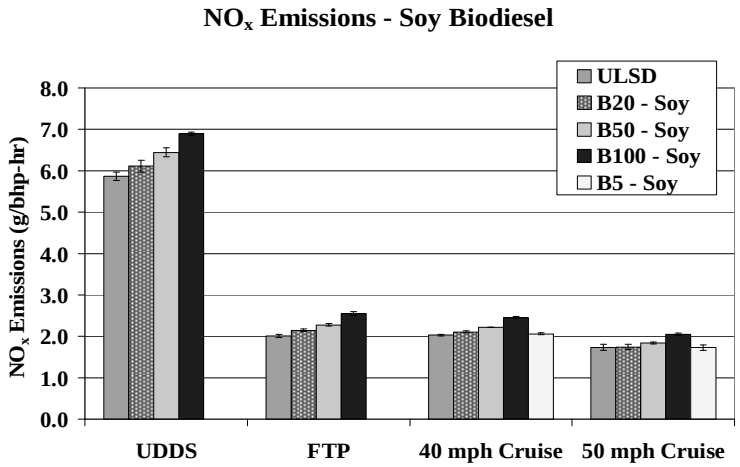
| Day 10 | | Day 11 | | Day 12 | | Day 13 | | Day 14 | |
|---|---|---|---|---|---|---|---|---|---|
| Fuel | Cycle | Fuel | Cycle | Fuel | Cycle | Fuel | Cycle | Fuel | Cycle |
| CARB | A | B20 | B | B50 | A | B100 | C1 | CARB | C1 |
| | C1 | | A | | B | | A | | C1 |
| | B | | C1 | | C1 | | B | | C1 |
| B20 | A | B50 | C1 | B100 | B | CARB | C1 | B5 | C1 |
| | B | | B | | C1 | | A | | C1 |
| | C1 | | A | | A | | B | | C1 |

| Day 16 | | Day 17 | | Day 18 | | Day 19 | | Day 20 | | Day 21 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Cycle | Fuel | Cycle | Fuel | Cycle | Fuel | Cycle | Fuel | Cycle | Fuel | Cycle |
| CARB | C | CARB | A | CARB | A | CARB | C | CARB | C | B50 | A |
| | A | | C | | B | | C | | C | | B |
| | B | | B | | C | | C | | C | | A |
| B20 | A | B50 | C | B100 | B | B5 | C | | C | | B |
| | C | | A | | A | | C | B20 | C | B100 | C |
| | B | | B | | C | | C | | C | | C |
| B20 | B | B50 | C | B100 | A | B5 | C | | C | | C |
| | A | | B | | C | | C | | C | | C |
| | C | | A | | B | | C | B50 | C | CARB | C |
| CARB | C | CARB | A | CARB | B | CARB | C | | C | | C |
| | B | | C | | C | | C | | C | | C |
| | A | | B | | A | | C | | C | | C |



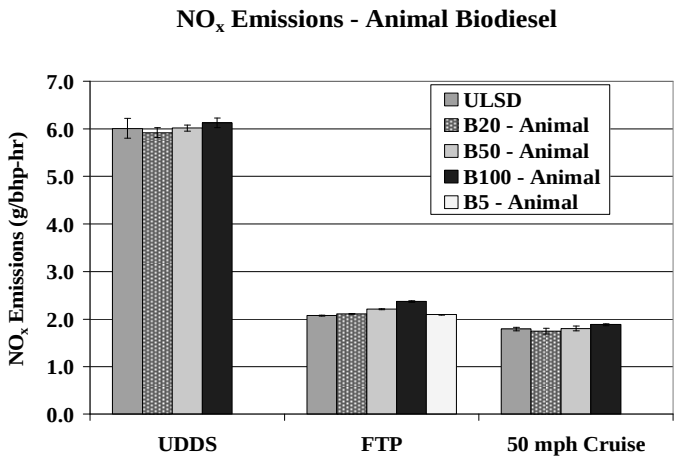


# Soy Biodiesel $NO_x$ Results 2006 Cummins



Biodiesel/Renewable Diesel Study

# Soy Biodiesel $NO_x$ Results 2006 Cummins



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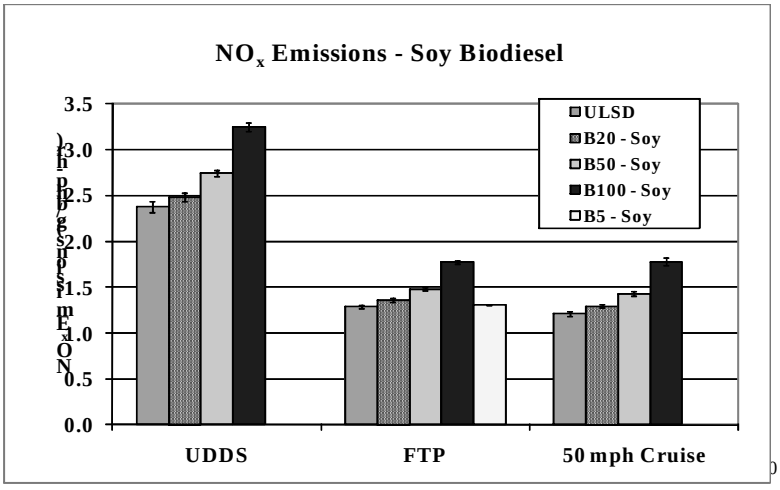
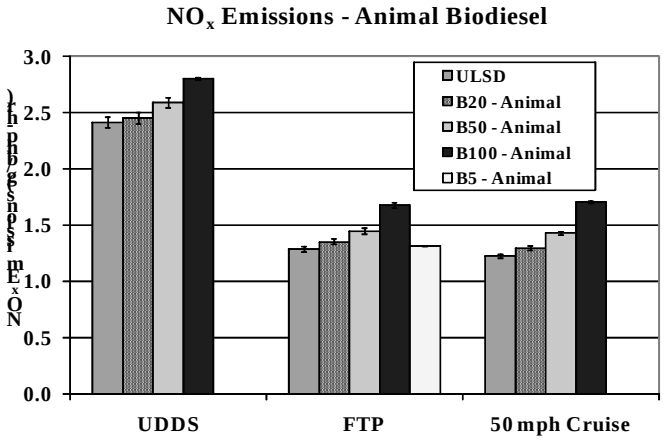
# Draft $NO_x$ Results 2007 MBE4000



Biodiesel/Renewable Diesel Study

# Draft $NO_x$ Results 2007 MBE4000



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# Draft Biodiesel $NO_x$ Engines 1 & 2

| | | 2006 Cummins ISM | | | | 2007 MBE4000 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Soy-based | | Animal-based | | Soy-based | | Animal-based | |
| | CARB vs. | % Difference | P-values | % Difference | P-values | % Difference | P-values | % Difference | P-values |
| UDDS | B20 | 4.1% | 0.002 | -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% | 0.243 | 36.6% | 0.000 | 16.0% | 0.000 |
| FTP | B5 | 2.2% (Mit) | 0.000 | 0.3% | 0.298 | 0.9% | 0.007 | 1.3% | 0.000 |
| | B10 | 2.6% (Mit) | 0.000 | | | | | | |
| | B20 | 6.6% | 0.000 | 1.5% | 0.000 | 5.9% | 0.000 | 4% | 0.000 |
| | 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 |
| 40 mph Cruise | B5 | 1.7% | 0.135 | | | | | | |
| | B20 | 3.9% | 0.000 | | | | | | |
| | B50 | 9.1% | 0.000 | | | | | | |
| | B100 | 20.9% | 0.000 | | | | | | |
| 50 mph Cruise | B5 | -1.1% | 0.588 | | | | | | |
| | B20 | 0.5% | 0.800 | -2.3% | 0.151 | 6.9% | 0.000 | 5.9% | 0.000 |
| | B50 | 6.3% | 0.001 | 0.8% | 0.588 | 18.2% | 0.000 | 16.3% | 0.000 |
| | B100 | 18.3% | 0.000 | 5.3% | 0.000 | 47.1% | 0.000 | 39.4% | 0.000 |

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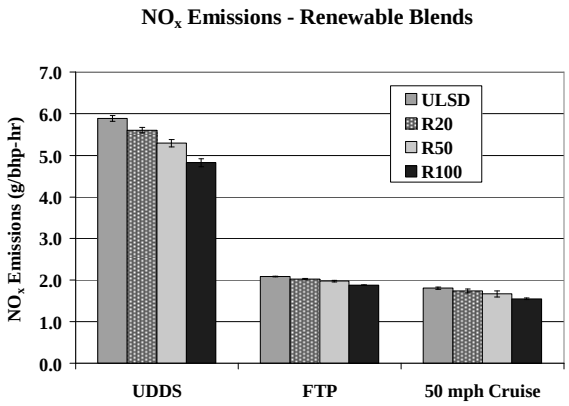
# Renewable $NO_x$ Results 2006 Cummins



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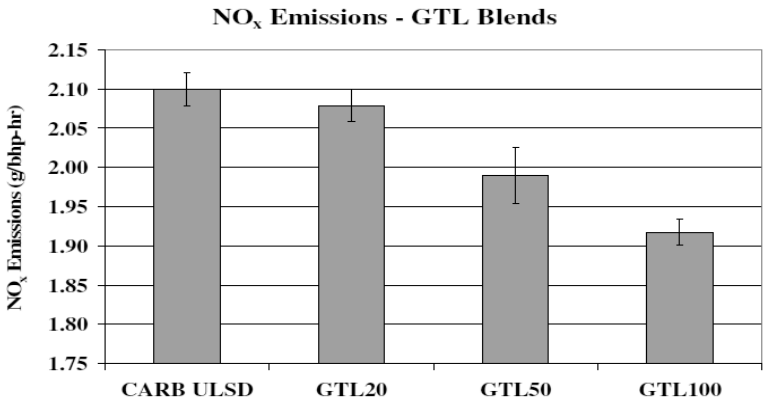
# GTL $NO_x$ Results 2006 Cummins



# Draft Renewable/GTL $NO_x$ 2006 Cummins

| | | Renewable | | GTL | |
|---|---|---|---|---|---|
| | CARB vs. | % 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 | | |





# Strategies for $NO_x$ Mitigation

– Additives
– Renewable/biodiesel blends
– GTL
– Match blending – subsequent testing??

# 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 $NO_x$ disbenefit
- All testing on FTP
- DTBP successful at 1% level with B20
- 2-EHN unsuccessful even at 1% level with B5
- Additional testing as needed to look at cycle effects and higher blend levels





# 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/B10-S, CARB80/R15/B5-S
  - CARB80/R13/B3S/B4A, CARB70/R10/B10-S .25DTBP
- Some blends w/ B10/B20 unsuccessful (Engine 1)
  - CARB70/R20/B10-S
  - CARB80/G10/B10-S, CARB80/G27/B20-S
- Engine 2
  - B5-S + 0.25% DTBP successful
  - CARB80/R15/B5-S unsuccessful

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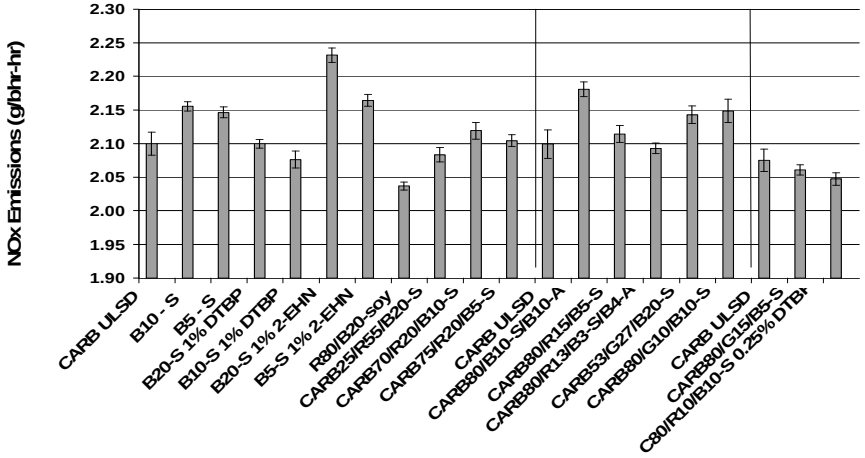
# $NO_x$ Mitigation 2006 Cummins



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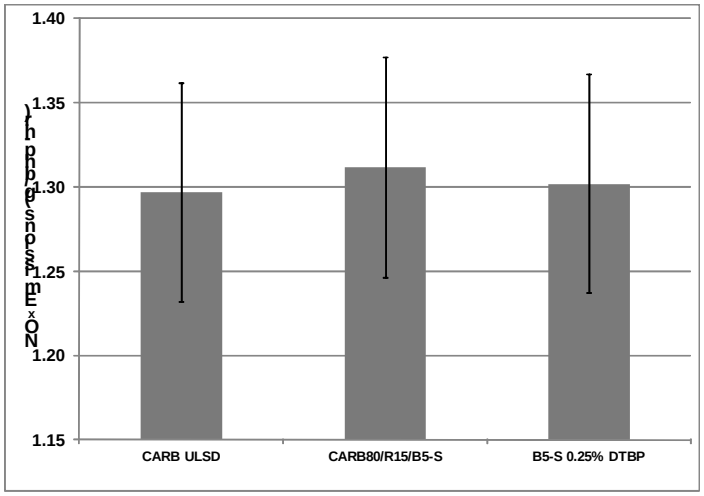
# Draft Engine 2 $NO_x$ Mitigation



# Draft $NO_x$ Mitigation Results

| CARB vs. | 2006 Cummins ISM % Difference | 2006 Cummins ISM P-values | 2007 MBE4000 % Difference | 2007 MBE4000 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 | | |
| CARB25/R55/B20-S | -0.8% | 0.029 | | |
| CARB70/R20/B10-S | 0.9% | 0.014 | | |
| CARB75/R20/B5-S | 0.2% | 0.674 | | |
| CARB80/B10-S/B10-A | 3.9% | 0.000 | | |
| CARB80/R15/B5-S | 0.7% | 0.117 | 1.1% | 0.029 |
| CARB80/R13/B3-S/B4-A | -0.3% | 0.501 | | |
| CARB53/G27/B20-S | 2.1% | 0.000 | | |
| CARB80/G10/B10-S | 2.4% | 0.000 | | |
| CARB80/G15/B5-S | -0.7% | 0.068 | | |
| CARB80/R10/B10-S 0.25% DTBP | -1.3% | 0.002 | | |
| B5-S 0.25% DTBP | | | 0.4% | 0.175 |

* From testing with soy-biodiesel feedstock





# Additional Mitigation Testing

- Second Phase of $NO_x$ mitigation testing planned
- Testing at CARB facility in Los Angeles

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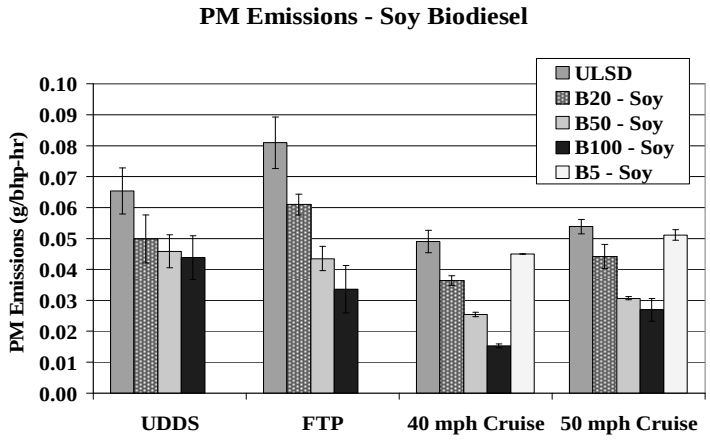
# PM Results 2006 Cummins



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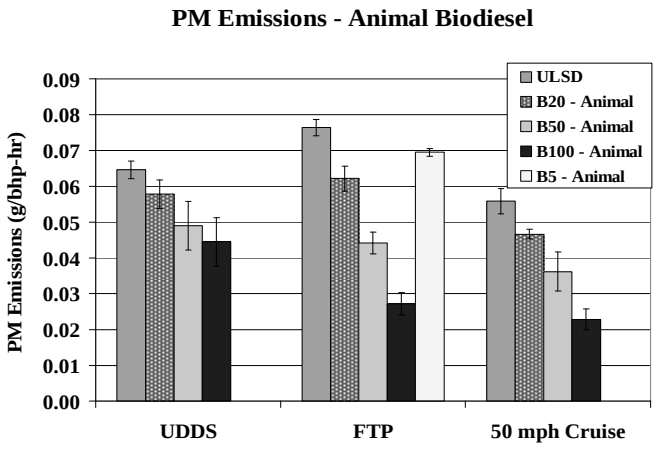
# PM Results 2006 Cummins



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# Draft PM Test Results

| | | 2006 Cummins ISM | | | | 2007 MBE4000 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Soy-based | | Animal-based | | Soy-based | | Animal-based | |
| | CARB vs. | % Difference | P-values | % Difference | P-values | % Difference | P-values | % Difference | P-values |
| UDDS | B20 | -24% | 0.002 | -24% | 0.002 | -94% | 0.187 | 224% | 0.779 |
| | B50 | -30% | 0.000 | -30% | 0.000 | 9% | 0.874 | 285% | 0.219 |
| | B100 | -33% | 0.000 | -33% | 0.000 | -37% | 0.470 | 1043% | 0.000 |
| FTP | B5 | -6% (Mit) | 0.000 | -6% (Mit) | 0.000 | -61% | 0.096 | -32% | 0.553 |
| | B10 | -17% (Mit) | 0.000 | -17% (Mit) | 0.000 | | | | |
| | B20 | -25% | 0.000 | -25% | 0.000 | -4% | 0.944 | -45% | 0.341 |
| | B50 | -46% | 0.000 | -46% | 0.000 | 58% | 0.216 | 15% | 0.757 |
| | B100 | -58% | 0.000 | -58% | 0.000 | 64% | 0.403 | -30% | 0.611 |
| 40 mph Cruise | B5 | -6% | 0.101 | -6% | 0.101 | | | | |
| | B20 | -26% | 0.000 | -26% | 0.000 | | | | |
| | B50 | -48% | 0.000 | -48% | 0.000 | | | | |
| | B100 | -69% | 0.000 | -69% | 0.000 | | | | |
| 50 mph Cruise | B5 | -5% | 0.036 | -5% | 0.036 | | | | |
| | B20 | -18% | 0.000 | -18% | 0.000 | -19% | 0.746 | -49% | 0.143 |
| | B50 | -43% | 0.000 | -43% | 0.000 | 2% | 0.970 | -58% | 0.103 |
| | B100 | -50% | 0.000 | -50% | 0.000 | -100% | 0.704 | -39% | 0.237 |



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# Draft THC Test Results

| | | 2006 Cummins ISM | | | | 2007 MBE4000 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Soy-based | | Animal-based | | Soy-based | | Animal-based | |
| | CARB vs. | % 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% | 0.683 | 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 | 19% | 0.376 |
| | B50 | -29% | 0.000 | -36% | 0.000 | 25% | 0.018 | -13% | 0.568 |
| | B100 | -63% | 0.000 | -71% | 0.000 | 20% | 0.081 | 11% | 0.756 |
| 40 mph Cruise | B5 | -1% | 0.573 | | | | | | |
| | 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 |

# Draft CO Test Results

| | | 2006 Cummins ISM | | | | 2007 MBE4000 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Soy-based | | Animal-based | | Soy-based | | Animal-based | |
| | CARB vs. | % Difference | P-values | % Difference | P-values | % Difference | P-values | % Difference | P-values |
| UDDS | B20 | 5% | 0.115 | -10% | 0.000 | -62% | 0.453 | 18% | 0.003 |
| | 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% (Mit) | 0.405 | -4% | 0.008 | -20% | 0.135 | -11% | 0.202 |
| | B10 | -2% (Mit) | 0.151 | | | | | | |
| | B20 | -3% | 0.078 | -7% | 0.000 | 13% | 0.534 | 1% | 0.841 |
| | B50 | -4% | 0.038 | -14% | 0.000 | -50% | 0.031 | -39% | 0.040 |
| | B100 | 3% | 0.163 | -27% | 0.000 | -74% | 0.002 | -72% | 0.000 |
| 40 mph Cruise | B5 | 2% | 0.427 | | | | | | |
| | 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 |