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

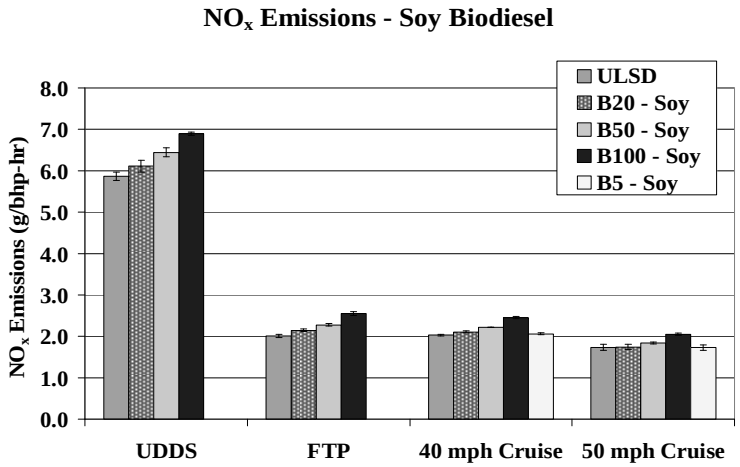
Soy based biodiesel

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

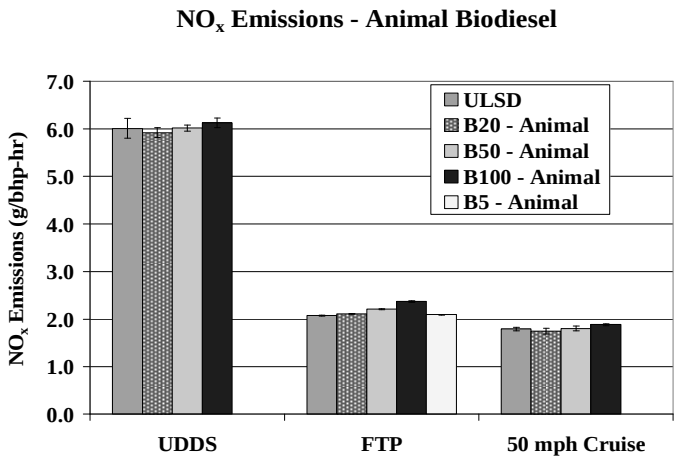
Day 16		Day 17		Day 18		Day 19		Day 20		Day 21	
Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle
CARB	C	CARB	A	CARB	A	CARB	C	CARB	C	B50	A
	A		C		B		C		C		B
	B		B		C		C		C		A
B20	A	B50	C	B100	B	B5	C		C		B
	C		A		A		C	B20	C	B100	C
	B		B		C		C		C		C
B20	B	B50	C	B100	A	B5	C		C		C
	A		B	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



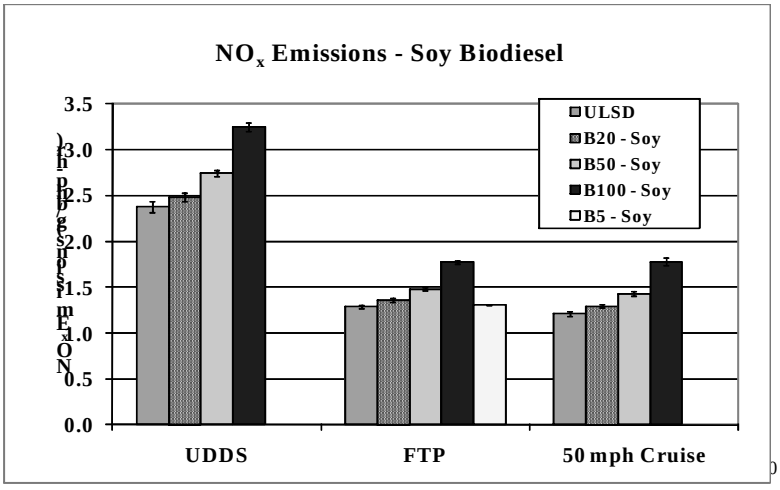
Biodiesel/Renewable Diesel Study

Soy Biodiesel NO_x Results 2006 Cummins



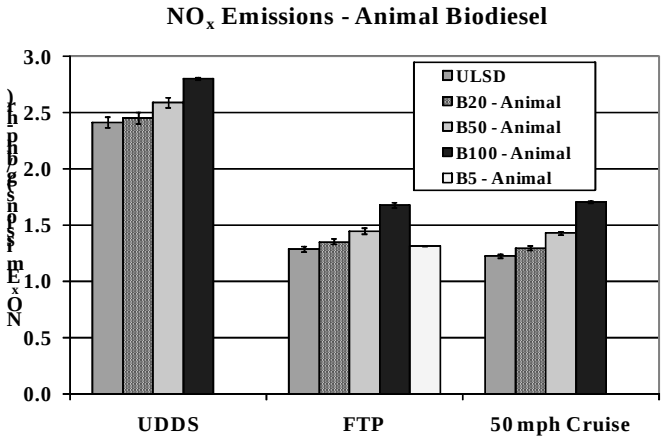
Biodiesel/Renewable Diesel Study

Draft NO_x Results 2007 MBE4000



Biodiesel/Renewable Diesel Study

Draft NO_x Results 2007 MBE4000



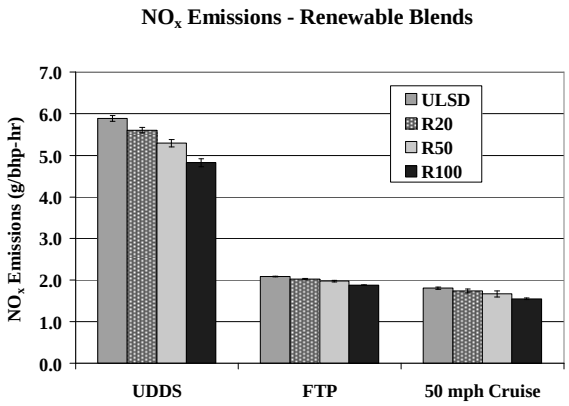
Biodiesel/Renewable Diesel Study

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

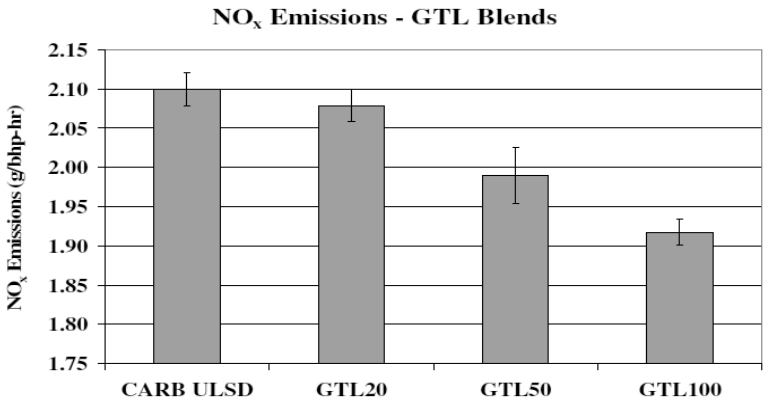
Biodiesel/Renewable Diesel Study

Renewable NO_x Results 2006 Cummins



Biodiesel/Renewable Diesel Study

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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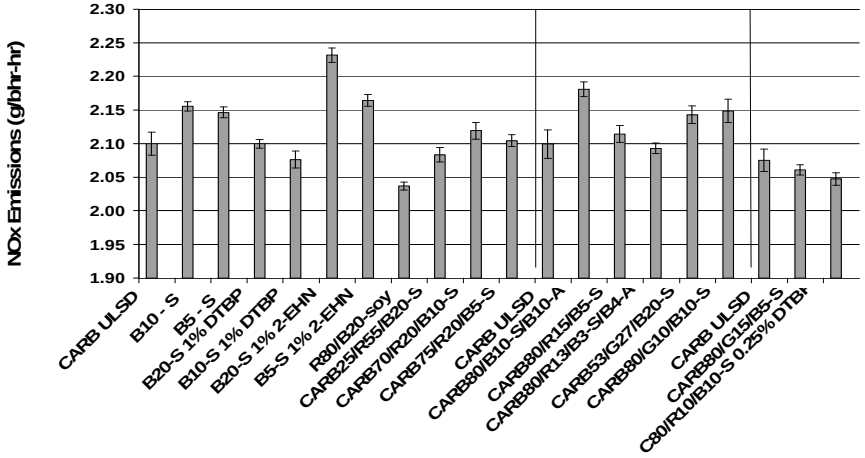
NO_x Mitigation 2006 Cummins



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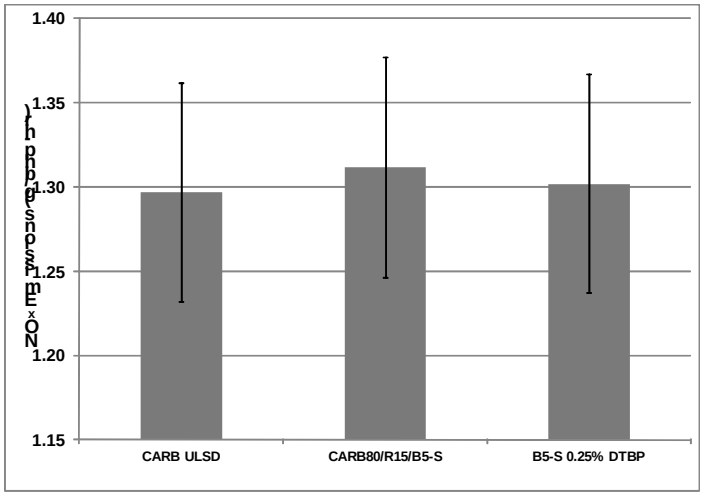
Draft Engine 2 NO_x Mitigation



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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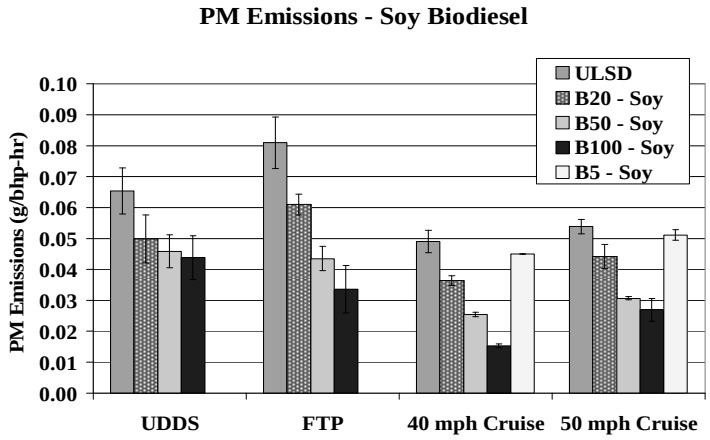
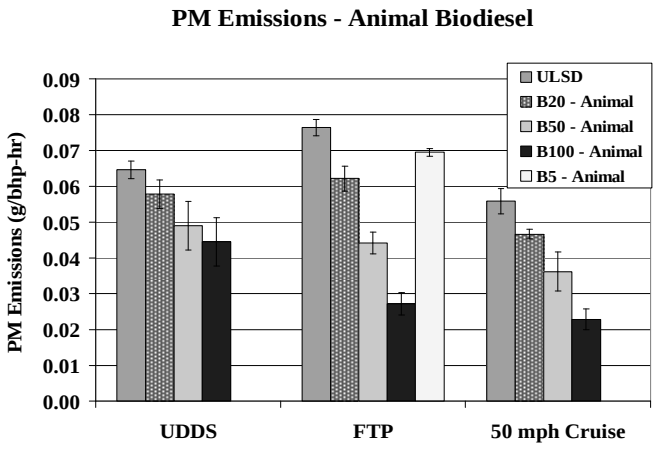
PM Results 2006 Cummins



Biodiesel/Renewable Diesel Study

PM Results 2006 Cummins



Biodiesel/Renewable Diesel Study

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

Biodiesel/Renewable Diesel Study

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