Biodiesel and Renewable Diesel Research Study

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California Environmental Protection Agency

Air Resources Board

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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_x 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_2O, 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/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_2O
- 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 (@ 60ºF)	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_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 both NO_x & PM
- CO_2 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_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

Soy Feedstock Test Matrix

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

Engine 1-2006 cummins ISM

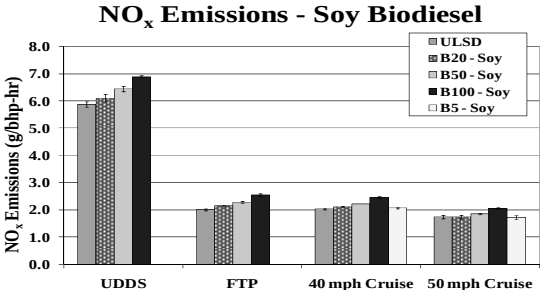
Soy based biodiesel

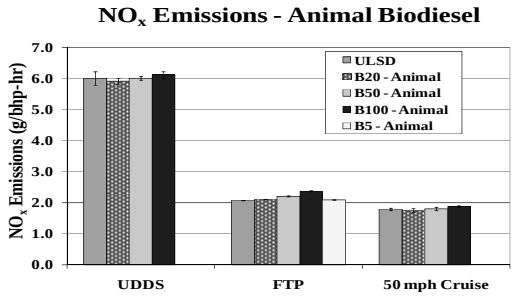
Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		Day 7		Day 8		Day 9		Day 10		Day 11		Day 12		Day 13		Day 14	
Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle
CARB	A	B20	B	B50	A	CARB	C1	B100	B	B20	C1	CARB	B	B50	A	B100	A	CARB	A	B20	B	B50	A	B100	C1	CARB	C1
	C1		A		B		A		C1		B		A		B		C1		C1		A		B		A		C1
	B		C1		C1		B		A		A		C1		C1		B		B		C1		C1		B		C1
B20	C1	B50	B	CARB	C1	B100	A	B20	B	CARB	A	B50	B	B100	C1	CARB	B	B20	A	B50	C1	B100	B	CARB	C1	B5	C1
	B		C1		A		B		A		C1		A		A		C1		B		B		C1		A		C1
	A		A		B		C1		C1		B		C1		B		A		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

Biodiesel/Renewable Diesel Study

NO_x Results 2006 Cummins





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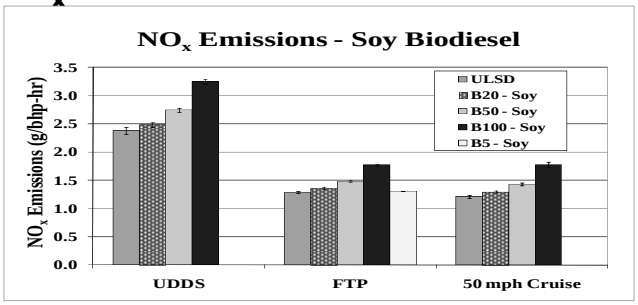
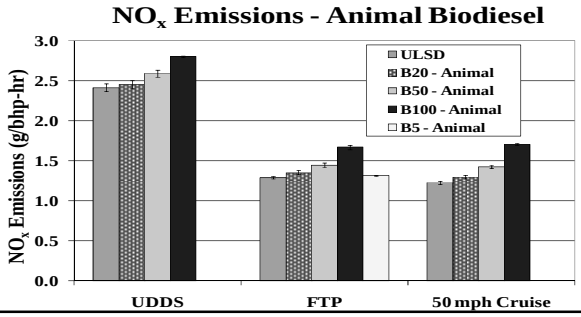
Biodiesel/Renewable Diesel Study

NO_x Results 2007 MBE4000





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Biodiesel NO_x Emissions Engines 1 & 2

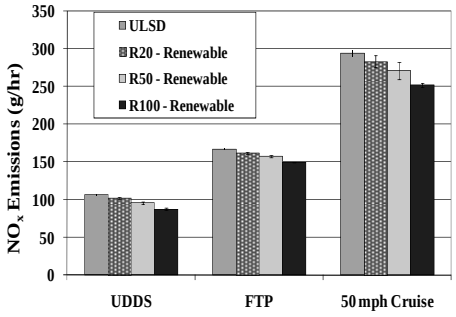
		2006 Cummins ISM				2007 MBE4000			
		Soy-based		Animal-based		Soy-based		Animal-based	
	CARB vs.	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	4.1%	0.002	-1.5%	0.376	4.4%	0.005	1.6%	0.000
	B50	9.8%	0.000	0.1%	0.935	15.3%	0.000	7.3%	0.000
	B100	17.4%	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	5.0%	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

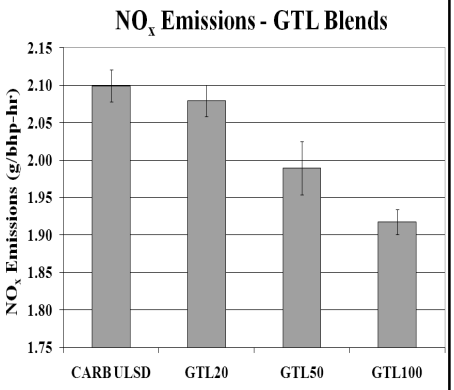
NO_x Characterization Summary

- NO_x increased with biodiesel for nearly test combinations
- NO_x increases larger than “average” EPA values
- NO_x increases larger for newer 2007 MBE4000 vs. 2006 Cummins
- NO_x increases as a function of load differed between engines
  - Highest NO_x impact for FTP for 2006 Cummins (complications with 50 mph cruise)
  - NO_x impacts for 2007 MBE4000 increased with increasing load
- Successful NO_x mitigation strategies included DTBP and renewable/GTL blends

Biodiesel/Renewable Diesel Study

NO_x Results 2006 Cummins





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Biodiesel/Renewable Diesel Study

Renewable/GTL NO_x Emissions 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		

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Strategies for NO_x Mitigation

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

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

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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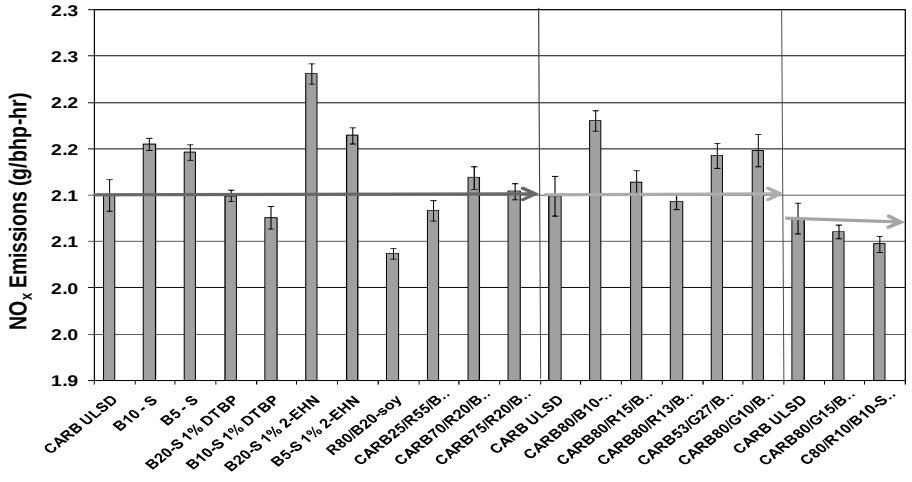
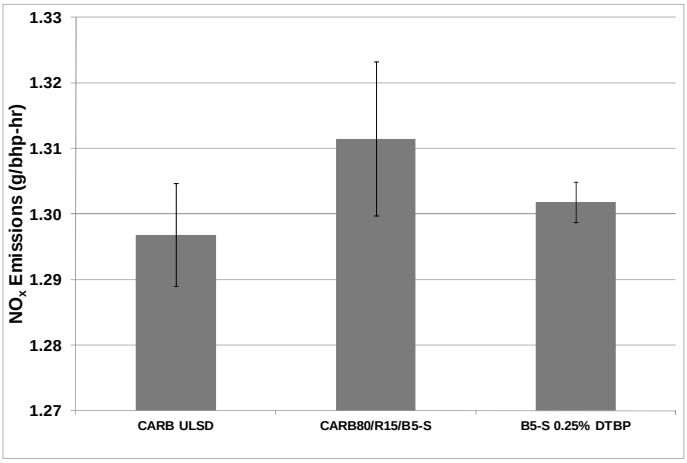
NO_x Mitigation
2006 Cummins ISM



NO_x Mitigation 2007 MBE4000



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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

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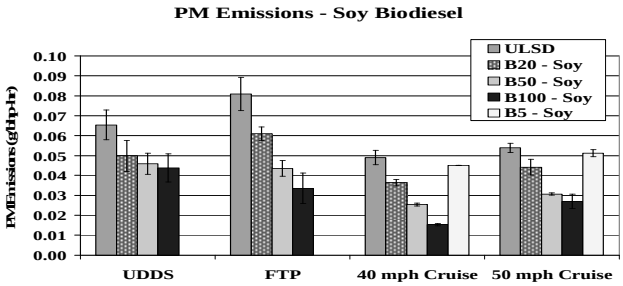
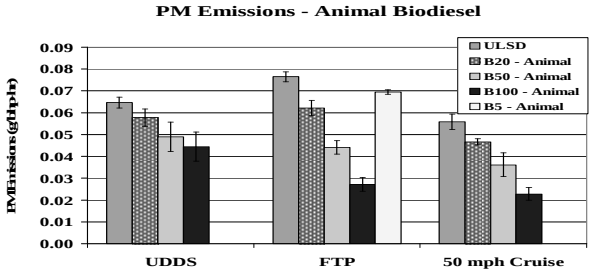
PM Results 2006 Cummins





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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℉

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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	-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				
	B20	-25%	0.000	-19%	0.000	-4%	0.944	40%	0.341
	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
40 mph Cruise	B5	-6%	0.101						
	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

		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	13%	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	5%	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

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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	-3%	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	-73%	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

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