Real-world Emissions From Private Diesel Passenger Vehicles Running On Unrefined Waste Vegetable Oil

Michal Vojtisek-Lom
Socharska 17, 170 00 Prague 7
Czech Republic
biodiesel.michal@seznam.cz

P. Joshua Wilson
Buffalo, New York, USA
pjwilson@mail.com

14th Coordinating Research Council Workshop on On-road Vehicle Emissions, San Diego, CA March 29-31, 2004

Abstract

Notably in the past decade there has been an increasing grassroots interest in running private diesel powered vehicles on various biofuels prepared from waste vegetable oil obtained from local restaurants. Two alternative strategies are being implemented. One strategy is an amateur conversion of waste grease to biodiesel, which is then used in lieu or in conjunction with diesel fuel, in a manner relatively similar to the large-scale use of commercially made biodiesel. The other strategy consists of the installation of an auxiliary fueling system utilizing unprocessed waste grease, without its conversion to biodiesel. The vehicle then operates in a bi-fuel mode - the engine is started and warmed up on the regular (diesel or biodiesel) fuel, while the auxiliary fueling system is heated to its operating temperature. Once this temperature is reached, the engine runs from the auxiliary tank, combusting waste grease.

While it has been previously documented that running diesel engines on straight vegetable oils can degrade the performance, reliability and longevity of diesel engines, such approach is becoming increasingly popular. There are at least two manufacturers of waste vegetable oil auxiliary fueling system conversion kits in the U.S., one claiming hundreds of successful installations on late-model diesel engines with minimal performance or reliability problems.

On-road data collected on a 1981 Volkswagen Vanagon suggested simultaneous NO_x, CO and PM reduction while running on waste vegetable oil compared to petroleum diesel. Laboratory data collected on a 2002 Volkswagen Golf shows that waste vegetable oil yielded consistenly lower NO_x emissions than petroleum diesel fuel, while CO and PM emissions have increased. (Both portable, on-board monitoring systems – OEM-2100 Montana System and SEMTECH-D – and laboratory instruments were used for measurements.) On-road data on a 2003 Volkswagen Jetta also suggests significant NOx reduction when running on waste grease.

Compared to biodiesel, waste vegetable oil is inexpensive, easily obtainable, and appears to yield lower NO_x emissions than both petroleum diesel and biodiesel. PM data is inconclusive, but it appears possible that any potential PM increases might be easily remedied by exhaust aftertreatment devices.

Waste vegetable oil as diesel engine fuel

- Diesel engine originally designed to run on vegetable oils
- Experiments on using vegetable oils as diesel engine fuel conducted in 1960’s and 1970’s, with mixed results

Waste vegetable oil from food industry is an increasingly popular feedstock for diesel engine fuel

- Plentiful resource (existing supply can displace 1-3% of U.S. diesel fuel use)
- Safe to handle (high flash point, non-toxic, readily biodegradable)
- Virtually zero sulfur content
- Virtually no aromatic content
- Inexpensive or free feedstock
- Domestic resource (important for national security and local economy)
- No greenhouse gas emissions (Kyoto protocol requires reduction of greenhouse gas emissions to below 1990 levels by 2010)

Two approaches to using waste vegetable oil

- Approach #1: Used as feedstock to produce Biodiesel fuel
- Approach #2: Straight vegetable oil (SVO) engine conversion

Waste vegetable oil vs. biodiesel

Biodiesel

- Produced (refined) from vegetable oil through chemical reaction with alcohol (trans-esterification)
- Can be burned in any diesel engine without modification
- Strong grassroots movement – home-made biodiesel production
- Commercial production of biodiesel widespread

Straight vegetable oil (SVO) conversion

- Filtered, but not chemically refined
- No need for refinery or other reactants (alcohol)
- Modification of engine necessary
  - Secondary SVO fueling system needs to be installed
  - SVO fueling system needs to be heated to lower SVO viscosity prior to injection
  - Engine needs to be started and warmed on conventional fuel
- Primarily grassroots movement
- Commercial conversion kit produced by several small companies

Biodiesel workshop, Superior, Montana, August 2001

- Grassroots workshop aimed at small scale, home biodiesel production
- Different vehicles were run on biodiesel brought by participants or produced on site
- 1981 VW Vanagon converted to SVO as part of workshop
- Real-world emissions testing conducted by authors on commercial and home-made biodiesel, diesel fuel and SVO

Report is given here on diesel, biodiesel and SVO comparison on 1981 VW Vanagon

Instrumentation

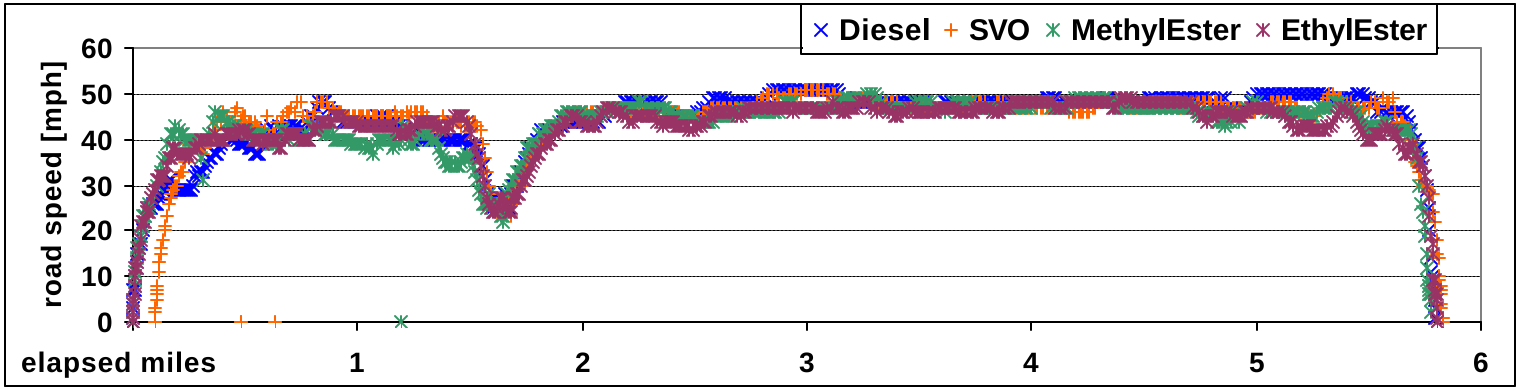
- **Custom portable, on-board emissions testing rig built by authors and transported to site as checked luggage**
- **HC, CO, CO_2, NO measured by dual repair-grade five-gas analyzers**
- **PM measured by light scattering**
- **Exhaust flow determined computationally**
- **System later commercialized by Clean Air Technologies as "Montana system" and described in detail elsewhere**
- **Monitoring system was installed in the vehicle and operated while vehicle was driven on the road**

Monitoring system in the passenger seat

Exhaust sampling probe and line

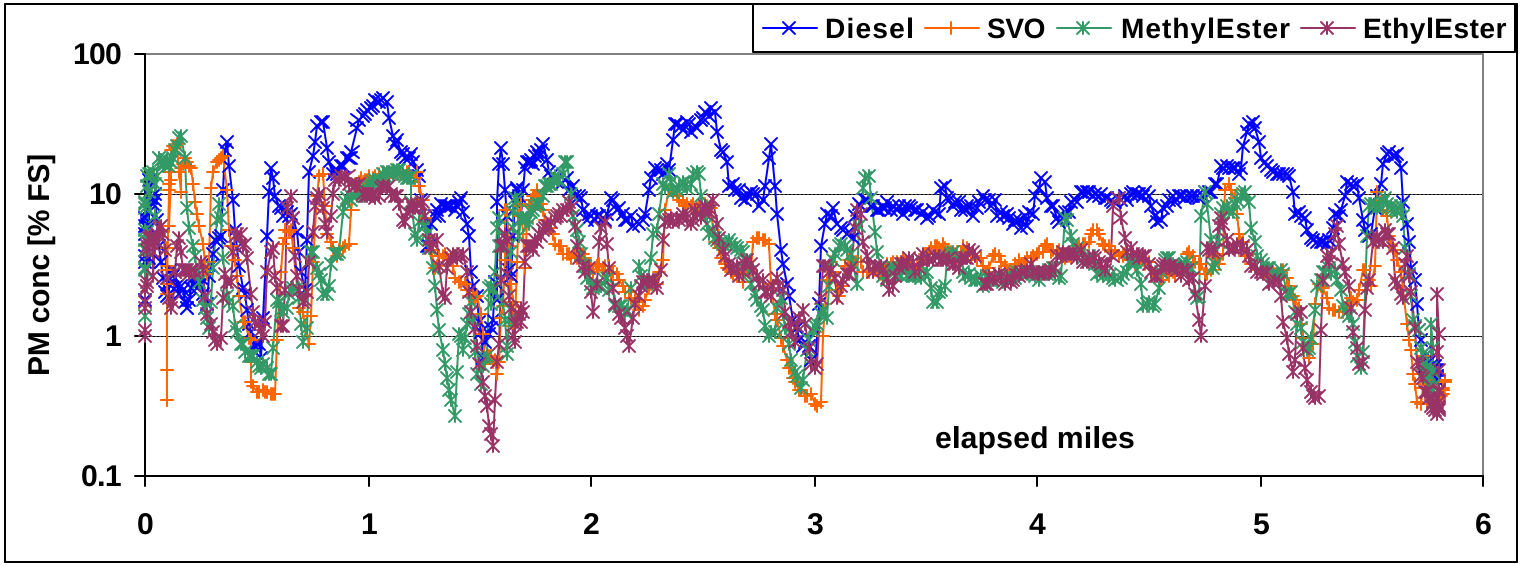
Real-time data

- Collected on a local road outside of Superior, MT
- Driving cycle data typically plotted against <u>time</u>
- Route data must be plotted against <u>distance</u> to be able to compare real-time data from multiple runs



GPS used for speed measurement

Speeds are comparable



Home-made methylester and commercial yellow mustard ethylester biodiesels used

PM concentrations are higher for diesel than for SVO or biodiesels

Composite data

Vehicle tested on a rural highway from Superior interstate highway exit to a four-way stop sign, and back

Tests were run on four fuels:

- **Diesel - street diesel fuel from a local pump**
- **SVO - straight vegetable oil placed in a heated tan**
- **ME - home-made methyl-ester of used vegetable oil**
- **EE - professionally made (Univ. of Idaho) ethyl-ester of yellow mustard seed oil**

Cumulative results, both absolute and relative to diesel are shown in table below

Westbound

	grams per test		
	NOx	CO	PM
Diesel	9.7	10.1	0.77
SVO	9.4	7.2	0.49
ME	10.7	7.9	0.50
EE	10.7	6.6	0.48

	Change relative to diesel		
SVO	- 3%	- 29%	- 37%
ME	+ 10%	- 22%	- 35%
EE	+ 10%	- 34%	- 37%

Eastbound

	grams per test		
	NOx	CO	PM
Diesel	9.5	7.5	0.58
SVO	9.8	5.8	0.34
ME	11.5	8.1	0.48
EE	11.3	5.1	0.40

	Change relative to diesel		
SVO	+ 3%	- 22%	- 41%
ME	+ 21%	+ 7%	- 17%
EE	+ 18%	- 32%	- 32%

2003 Laboratory testing

- 2002 Volkswagen Golf with 1.9-liter TDI engine tested on a chassis dynamometer at the New York State Dept. of Environmental Conservation laboratory in Latham, NY
- Vehicle equipped with commercially produced SVO conversion kit by Grease Car
- Conversion installed on new vehicle; 30,000 miles accumulated
- Engine control module reprogrammed for higher power output, aftermarket oversize injectors installed – not a SVO-related change
- I/M 240, LA-505 and Highway Fuel Economy driving cycles
- Main purpose of testing was to compare four designs of particulate matter monitoring instruments

Three test fuels:

- Street diesel (in the tank)
- Commercial 100% biodiesel (NOCO Energy, Tonawanda, NY); fed from a separate container
- Used Vegetable Oil (courtesy of Justin Carven); fed from a heated SVO tank

Instrumentation

- Various instrumentation used during the testing
- Data presented here has been obtained using portable systems
  - SEMTECH-D, Sensors Inc., Saline, MI
  - OEM-2100 Montana System, Clean Air Technologies Inc., Buffalo, NY

Data reported here obtained as follows:

- Exhaust flow: Computed from OBD-II data (OEM-2100)
- total HC: FID (SEMTECH-D)
- CO, CO2: NDIR (SEMTECH-D)
- NO: series of electrochemical cells (OEM-2100)
- PM: laser light side-scattering (OEM-2100)

SEMTECH-D

OEM-2100

Composite data

- Diesel, SVO (grease) and biodiesel (B100) fuels
- I / M 240, LA-505 and Highway Fuel Economy driving cycles

Total emissions [grams per test]

I/M 240	NOx	HC	CO	CO2	PM
Diesel 1	2.53	0.26	0.96	449	0.050
Diesel 2	2.42	0.26	0.88	450	0.054
Diesel 3	2.47	0.20	0.62	454	0.052
Diesel 4	2.31	0.22	0.69	451	0.052
Grease 1	1.92	0.37	1.34	448	0.074
Grease 2	1.83	0.31	1.20	446	0.077
Grease 3	1.88	0.35	1.49	462	0.092
Grease 4	1.84	0.34	1.55	453	0.095
Grease 5	1.83	0.34	1.44	467	0.103
Grease 6	1.76	0.34	1.34	463	0.108
B100 1	2.31	0.11	0.82	435	0.039
B100 2	2.34	0.10	0.77	443	0.037
B100 3	2.28	0.09	0.68	430	0.035
B100 4	2.36	0.10	0.77	436	0.034

LA-505	NOx	HC	CO	CO2	PM
Diesel	4.10	0.39	1.52	769	0.097
Grease	3.01	0.42	1.84	736	0.182
B100	3.86	0.14	1.16	703	0.057

HwyFET	NOx	HC	CO	CO2	PM
Diesel	7.47	0.40	2.54	1430	0.182
Grease	5.51	0.47	2.63	1373	0.259
B100	7.28	0.26	2.47	1397	0.105

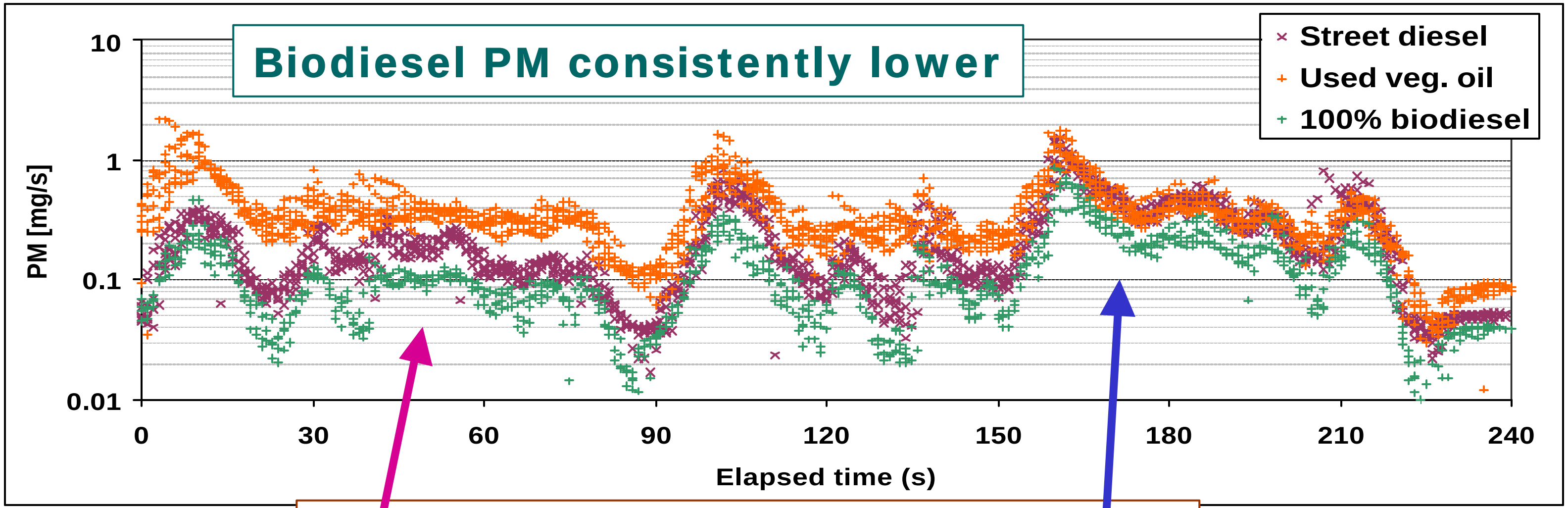
Emissions relative to diesel fuel

Grease vs. diesel fuel					
	NOx	HC	CO	CO2	PM
I/M240	- 24%	+ 46%	+ 77%	+ 1%	+ 76%
LA-505	- 27%	+ 8%	+ 21%	- 4%	+ 88%
HwyFET	- 26%	+ 17%	+ 4%	- 4%	+ 42%

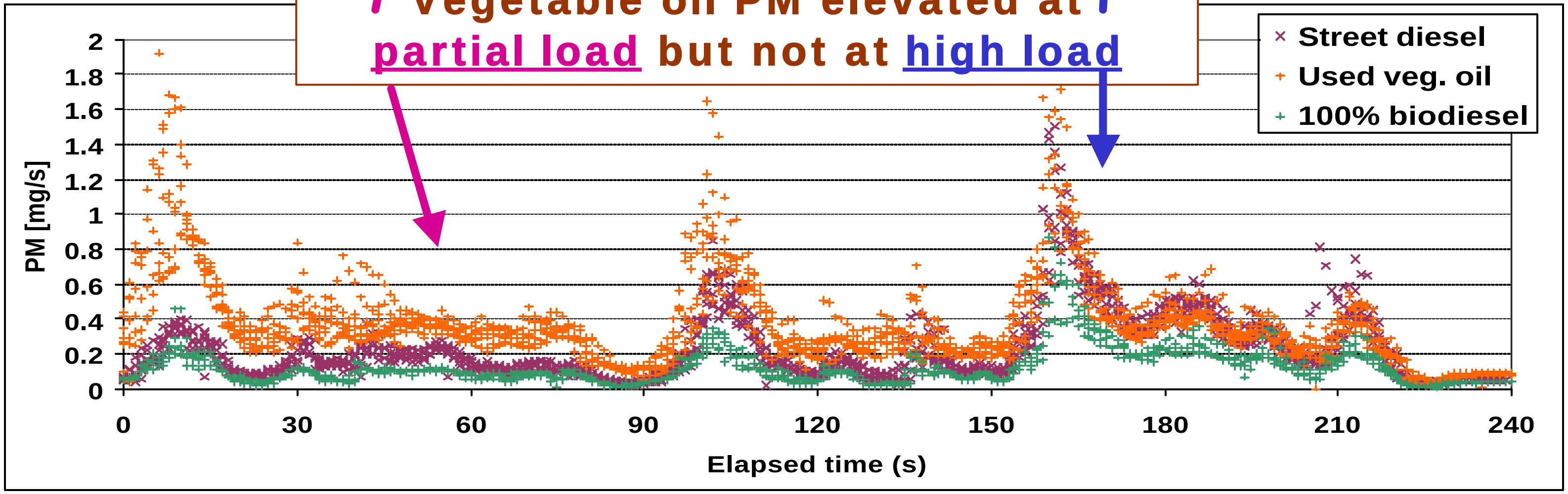
100% biodiesel (B100) vs. diesel fuel					
	NOx	HC	CO	CO2	PM
I/M240	- 5%	- 57%	- 3%	- 3%	- 30%
LA-505	- 6%	- 63%	- 24%	- 9%	- 41%
HwyFET	- 3%	- 36%	- 3%	- 2%	- 42%

Real-time PM data

I / M 240 cycle runs on diesel, biodiesel and used vegetable oil (SVO)
4-6 cycles were run for each fuel



Vegetable oil PM elevated at partial load but not at high load



Test-to-test variance for runs on street diesel: < 10 % for total PM mass

2004 testing at the CRC conference (March 29, 2004)

- **2003 Volkswagen Jetta, 11,300 miles**
- **Stock 1.9-liter 4-cylinder TDI engine**
- **Vehicle equipped with catalyst**
- **Vehicle equipped with commercially produced SVO conversion kit by Grease Car**

- **Vehicle was tested on a local test route, from Hyatt Islandia on Quivira Road to the I-5 Old Town exit and back, 7.14 miles round trip**

Three fuels used:

- **B-20 mix – 20% biodiesel, 80% petroleum diesel fuel (base fuel in original vehicle tank)**
- **Used vegetable oil from a restaurant (in a heated auxiliary tank)**
- **Virgin raw soybean oil (in a heated auxiliary fuel tank)**

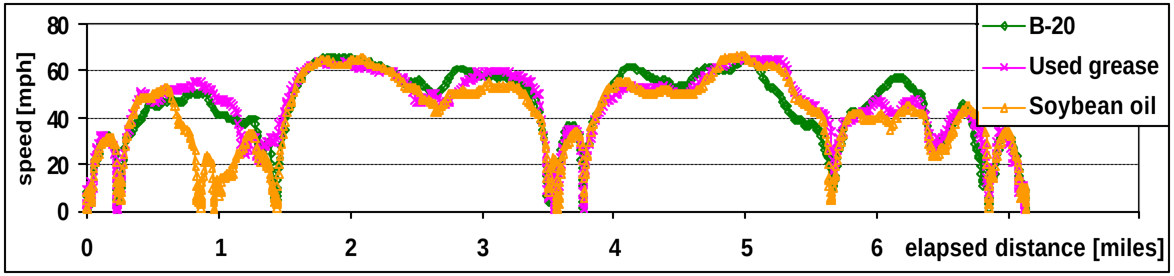
2004 testing – Composite data

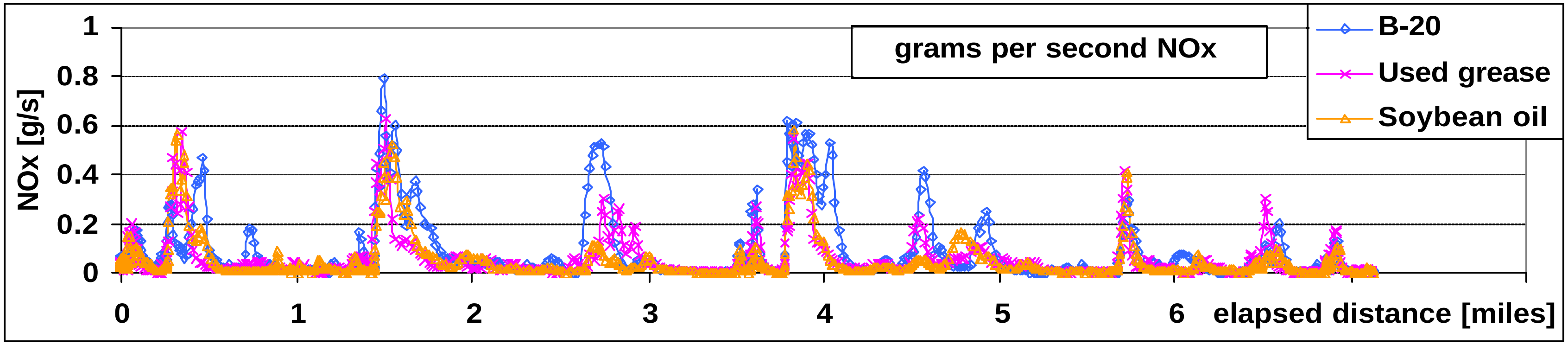
- Three runs: B-20 biodiesel blend, used grease and virgin soybean oil
- Engine was either shut off or idled for ~2 hours prior to the first run
- Traffic jam encountered during the third run
- To separate operating temperature and traffic jam effects, totals were calculated for three segments of the test

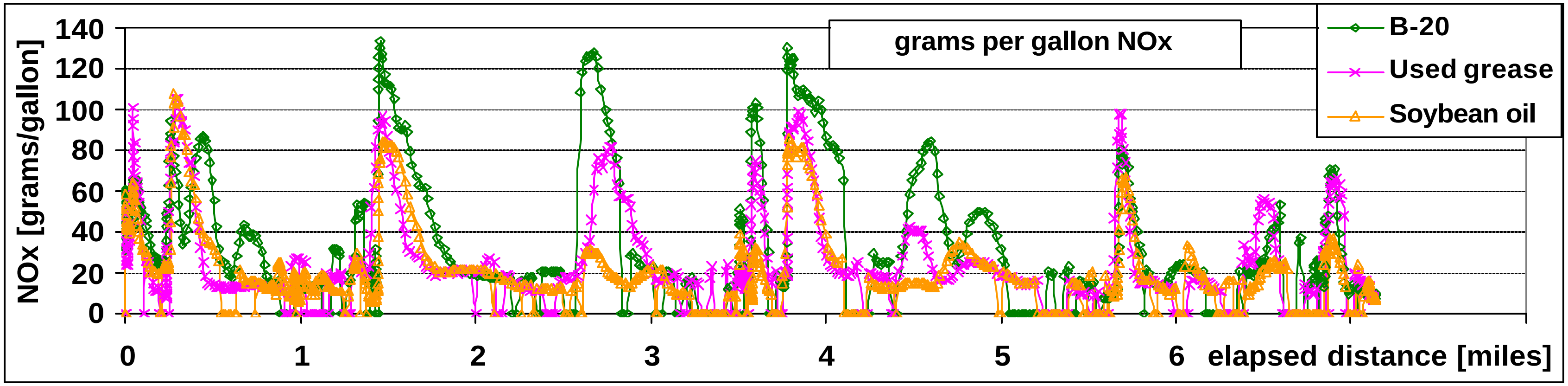
Segment	Fuel	Measured emissions, grams per test						Difference relative to B-20			
		NOx	HC	CO	CO2	PM	NOx	HC	CO	CO2	PM
All	B-20	57.41	9.56	6.20	10891	0.693					
7.14 miles	Grease	41.43	4.98	2.23	10625	0.612	- 28%	- 48%	- 64%	- 2%	- 12%
	Soy Oil	40.83	5.53	3.45	12028	0.915	- 29%	- 42%	- 44%	+ 10%	+ 32%
Start to	B-20 (1)	12.84	4.10	5.23	2851	0.203					
1.45 miles	Grease	11.36	1.37	0.93	2730	0.164	- 12%	- 67%	- 82%	- 4%	- 19%
	Soy Oil (2)	13.42	1.19	3.04	3615	0.346	+ 5%	- 71%	- 42%	+ 27%	+ 70%
1.45-3.58	B-20	17.83	1.75	0.21	2842	0.163					
	Grease	10.77	1.29	0.31	2613	0.144	- 40%	- 26%	+ 46%	- 8%	- 12%
	Soy Oil	10.38	1.39	0.18	2885	0.176	- 42%	- 20%	- 16%	+ 2%	+ 8%
3.58 miles	B-20	26.74	3.71	0.76	5198	0.327					
to end	Grease	19.30	2.32	0.99	5282	0.304	- 28%	- 38%	+ 31%	+ 2%	- 7%
	Soy Oil	17.03	2.96	0.23	5528	0.393	- 36%	- 20%	- 69%	+ 6%	+ 20%
(1)	Engine was idled and shut off for a period prior to test; emissions during this portion could have been increased as a result.										
(2)	Traffic jam encountered approx. 1 mile into the test run; emissions and fuel consumption may have been increased as a result										

2004 testing – Real-time data

- **Comparison of real-time data done on distance basis; time basis does not allow for comparison**
- **NOx emissions on grease/oil lower primarily at high loads (accelerations)**







Discussion (1)

Emissions

- No apparent changes in driveability or power were observed among fuels
- SVO NO_x emissions were unchanged (Vanagon) or dramatically lowered (Golf and Jetta); biodiesel NOx were increased on Vanagon, but lowered on Golf
- PM, HC and CO emissions were consistently lowered on Vanagon, consistently higher on Golf, inconclusive on Jetta – but Jetta used B-20 as base fuel, and B-20 has been known to produce lower PM, HC and CO than petroleum diesel
- Investigation of real-time data on Golf suggests running on SVO increased PM emissions at low-load, but not at high-load operation
- But PM, HC and CO can be easily lowered by the use of diesel oxidation catalysts or particulate traps; SVO is ultra-low sulfur fuel
- Jetta data exhibit significant decrease in NOx when running on grease or oil compared to B-20, primarily at high loads

Sampling

- Results were very preliminary, only three vehicles were tested
- These vehicles might have been a good representative of the “fleet”, but not of the general vehicle population:
  - 1981 Vanagon was a high-mileage vehicle in marginal mechanical condition; several series of tests had to be discarded because of engine malfunctions
  - 2002 VW Golf was custom modified (oversize injectors and Wetterhuer “chip” – engine control module reprogramming for higher power) and exhibited very high overall PM levels
- 2002 Golf and 2003 Jetta were equipped with OEM catalyst; measurements of engine-out (before catalyst) emissions were not performed

Discussion (2)

Deterioration

- Running diesel engine on raw oils at ambient temperature has been reported to lead to coking, deposits and injection pump failures, likely related to high viscosity
- Heating of the fuel to lower the viscosity allegedly alleviates these problems if done in a careful, controlled and appropriate manner. Grease Car reports hundreds of vehicles converted, with minimal engine or fueling system problems; but few of the vehicles accumulated mileages comparable to useful engine life
- Deterioration of the vehicles was partially addressed; 1981 Vanagon was recently converted, 2002 Golf has been converted when new and has accumulated approximately 30,000 miles
- More detailed investigation of engine (particularly injection pump) reliability needs to be conducted as converted vehicles accumulate mileage

Straight vegetable oil conversions appear to be where CNG and propane conversions were in their initial stages. SVO is a domestic, renewable, inexpensive fuel, with virtually zero greenhouse gas emissions and a good potential to reduce regulated emissions.

Future research focus

- Pre-catalyst measurements; observed NOx reduction may be attributable to the catalyst
- Measurements on engines with high accumulated mileage to evaluate deterioration effects

Conclusions

- Emissions were measured on two diesel-powered private passenger vehicles, 1981 VW Vanagon and 2002 VW Golf, that have been retrofitted with a heated fueling system allowing combustion of raw (straight) used vegetable oil
- Test results are preliminary, as only two vehicles were tested
- On VW Vanagon, no significant change in NOx, and a substantial reduction in PM, HC and CO was observed
- On VW cars, NOx was reduced significantly (~25%); PM, HC and CO were increased on one car, but possibly reduced on other car
- Based on the limited test data, SVO has a potential as a domestic, renewable, inexpensive fuel, with virtually no greenhouse gas emissions; unlike biodiesel it does not increase NO_x; effect on PM, HC and CO needs additional evaluation, but these can be reduced by existing technologies
- SVO conversion technology is in an early stage, additional tests and fleet aging will bring more answers about emissions and reliability

Acknowledgments

This is private research conducted by the authors.
Help and in-kind donations, as listed below, were greatly appreciated.
No monetary compensation was received from any source.

2001 testing

- Justin Carven, GreaseCar (Florence, MA) – motivation, technical advice, conversion kits, test fuel
- David Max (Missoula, Montana) – Biodiesel 2001 workshop organizer; loan of test vehicle; test fuels
- Joe Thomson, Univ. of Idaho at Moscow – test fuel
- NYSETI (Rome, NY), University of Pittsburgh (Pittsburgh, PA), TSI (St. Paul, MN), Andros Inc. (Berkeley, CA), New York State Dept. of Environmental Conservation, New York City Dept. of Transportation – loan of monitoring system components

2003 testing

- Aaron Pulaski and Dr. Thomas Lanni, NYS DEC (Latham, NY) – access to laboratory and use of SEMTECH-D and OEM-2100 portable systems; test data
- Scott McGrath (Randolph, Vermont) – loan of test vehicle; dynamometer driving
- Justin Carven, GreaseCar – test fuel, management, advice

2004 testing

- Tony Thorpe (San Diego, CA) – loan of and driving of test vehicle, test fuel