Influences of alternative diesel fuels on tailpipe emissions and particulate matter under the highway fuel economy test cycle

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Abstract
Diesel engine vehicles are widely used worldwide in community and goods transport sectors due to their engine’s high efficiency and durability. Despite continuous improvements in various aspects, the combustion of compression ignition in conventional diesel engine is yet an important source of pollution and particulate matter that causes issues to human health and the environment. The objective of this research work is to study the use of conventional diesel (B7), biodiesel (B10) and premium diesel (DHi) fuels that affects to the release of exhaust gas and particulate matter emissions from tailpipes during a Highway Fuel Economy Test (HWFET) cycle. The experimental results have shown that the combustion of B7 and B10 reduced particulate matter by 0.38% and 51.0%, reduced total unburned hydrocarbon by 25.3% and 28.3%, reduced carbon monoxide by 43.3% and 64.0%, and reduced nitric oxide by 6.0% and 16.5%, respectively compared to DHi baseline on mass basis. The vehicle running on B10 releases a higher particle concentration with a smaller size compared to DHi.

Keywords: Biodiesel, Diesel, Emission, HWFET, Particulate matter.

1. Introduction
Among various atmospheric pollutants, there are major sources associated with human respiratory diseases. A number of studies founded that biomass burning and secondary particulate matter are as a result of the combined reaction of automotive exhaust and ammonia from agricultural fertilizers [1]. Diesel engine vehicles are widely used worldwide in community and goods transportation sectors due to their engine’s high efficiency and durability. Statistically, numbers of diesel vehicles registered throughout the world increase year by year. The most pollutants in diesel engines are nitrogen oxides ($NO_x$) and particulate matter (PM). The main cause of the pollutant is from the incomplete combustion of the diesel engine. The pollutants will affect the lower respiratory tract when inhaled causing illness and affect the environment [2].

Armas et al. (2013) [3] studied the potential of two alternative fuels (biodiesel and gas-to-liquid (GTL) synthetic diesel), and diesel under the New European Driving Cycle (NEDC) that significantly affects the formation of pollutant emissions. The experimental results have shown that total unburned hydrocarbon (HC) and carbon monoxide (CO) were reduced with alternative fuels, especially during the first urban cycle. These trends suggest that the composition of alternative fuels favors a cleaner
combustion. In the case of NO\textsubscript{x} emissions, similar results were observed between diesel and GTL; a slight decrease was obtained with biodiesel during most of NEDC, except in the last part of the cycle.

Macor et al. (2011) [4] assessed the two Euro-3 commercial trucks fueled with a 30% v/v biodiesel/diesel blended fuel (B30) and pure diesel fuel in laboratory under the standard driving conditions (Urban Driving Cycle, UDC, and Extra Urban Driving Cycle, EUDC) and the Common Artemis Driving Cycles (CADC) “URBAN” test cycle. The core of this paper is the measurement of regulated emissions (CO, NO\textsubscript{x}, HC and PM). Among the results from these tests, the substitution of diesel with B30 blend causes an increase in CO by 20% and HC by 20%. These increments were particularly evident in the UDC cycle. The NO\textsubscript{x} emissions showed higher level during URBAN cycle when driving condition was heavier with more acceleration phases. The PM produced by B30 was nearly 30% lower for both vehicles.

Lapuerta et al. (2015) [5] tested a new advanced biofuel-FAGE (fatty acid formal glycerol ester) produced from crude glycerol blended with diesel fuel (20% FAGE content) in an automotive engine following the New European Driving Cycle (NEDC). FAGE blend and the reference fuel showed similar NO\textsubscript{x} emissions, independent on the engine temperature while a substantial reduction (approx. 20-40%, with the highest reduction at warm engine temperature) of soot and particulate matter was observed for the FAGE blend. The FAGE bonded oxygen, higher than that of common biodiesel fuels, favors a complete combustion, therefore reducing these emissions.

Gao et al. (2019) [6] tested for the fuel consumption and exhaust emissions of a Euro-6 compliant light-duty diesel vehicle in Worldwide Harmonized Light Vehicles Test Cycles (WLTC) on a chassis dynamometer. The results showed that the exhaust emissions in the first 300 s dominated the accumulative emissions of the whole cycle; they were 63.2%, 55.4% and 56.0% of the total emissions for HC, NO\textsubscript{x} and CO, respectively. In the last 200 s of the cycle, increasing NO\textsubscript{x} emissions resulted from the high in-cylinder temperature despite of high catalyst efficiency.

The purpose of this paper is to investigate the use of conventional diesel (B7), biodiesel (B10) and premium diesel (DHi) fuels in a common rail diesel engine vehicle. These fuels have been widely used in the local market of Thailand. The trial was conducted under the Highway Fuel Economy Test (HWFET) cycle. By this scheme, the gaseous emissions, particulate matter and particle number-size distribution will be quantified and presented.

2. Materials and Method

2.1 Vehicle engine and equipment
The experimental tests were carried out using a 4-stroke, turbocharged diesel engine (Isuzu, Model 4JK1-TC), equipped with a common rail direct injection system. Its main specifications are shown in Table 1 and Figure 1 show the vehicle and equipment arrangement for the test.

| Table 1. Specifications of the test engine |
|---------------------------------|--------------|
| Item                            | Specification |
| Fuel type                       | Diesel       |
| Number of cylinder              | 4            |
| Displaced volume                | 2,499 cm\textsuperscript{3} |
| Maximum torque                  | 280 Nm @ 1,800-2,200 rpm |
| Maximum power                   | 85 kW @ 3,600 rpm |
| Bore · stroke                   | 87.4 mm · 95.4 mm |
| Compression ratio               | 18.3         |
The test of exhaust gas and particulate matter during Highway Fuel Economy Test (HWFET) cycle was based on chassis dynamometer (Maha, Model LPS3000). Tailpipe exhaust emissions such as CO, NO, HC, and smoke opacity were measured by emission tester (MAHA, Model MET 6.3). Smoke opacity was then converted to PM emission by calculation regarding the scheme explained by AVL in [7]. Meanwhile, particle number concentration and size distribution were measured by optical particle sizer (TSI, Model OPS 3330) with the measuring range between 300 and 10,000 nm.

2.2 Test conditions
The experimental procedure was accomplished based on Highway Fuel Economy Test (HWFET or HFET) cycle, a chassis dynamometer driving schedule developed by the U.S. Environmental Protection Agency (U.S. EPA) for the determination of fuel economy of light duty vehicles [8]. Additionally, the HWFET cycle simulates freeway travel and makes no complete stops until the end of the test cycle; details are shown in Table 2 [9]. The tests on each type of fuels were triplicate and replacement of the fuel filter during fuel changing was always accomplished.

### Table 2. U.S. EPA HWFET cycle details [9]

| Driving schedule attributes         | HWFET  |
|-------------------------------------|--------|
| Top speed                           | 96.6 km/h |
| Average speed                       | 77.7 km/h |
| Maximum acceleration                | 5.1 km/h/s |
| Distance covered                    | 16.6 km |
| Time elapsed                        | 12.75 min |
| Individual full stop                | 0      |
| Percentage of time stopped          | 0      |

2.3 Test fuels
In this research work, three types of fuel were used in the test: conventional diesel (B7), biodiesel (B10) and premium diesel (DHi). Selected properties of the test fuels are enumerated in Table 3.
Table 3. Fuel properties

| Properties                  | Premium diesel (DHi) | Conventional diesel (B7) | Biodiesel (B10) |
|-----------------------------|----------------------|--------------------------|-----------------|
| Density at 15°C (g/mL)      | 0.8217               | 0.8328                   | 0.8339          |
| Viscosity at 40°C (mm²/s)   | 3.475                | 2.882                    | 2.912           |
| Cetane index                | 61                   | 56                       | 56.2            |
| Flash point (°C)            | 97                   | 64                       | 62              |
| Water and sediment (% v/v)  | 0.1                  | 0.02                     | 0.02            |
| Lower heating value (MJ/kg) | 45.45                | 45.02                    | 44.72           |

3. Results and Discussion

3.1 Vehicle performance

Figure 2 shows the profiles of actual vehicle speed registered during the test of HWFET cycle with different fuels. These results were controlled to be similar with the cycle pattern for all fuels.

![Figure 2. Actual vehicle speed under HWFET cycle](image)

3.2 Exhaust emissions

The exhaust gas emissions described in this section are associated with HC, CO, and NO.

3.2.1 Total unburned hydrocarbon

Figure 3 shows time evolution of HC concentration during HWFET with the three fuels tested. It is clearly shown that the combustion for all the three fuels in this vehicle engine emitted very low HC concentration throughout the cycle. The results showed that the HC concentration characteristics of the are similar for all fuels. The maximum HC concentrations for DHi, B7 and B10 are by 12, 9 and 11 ppm, respectively. On mass basis in the unit of g/km, the accumulative HC emission during HWFET cycle from the vehicle running on the test fuels are in the order of B10<B7<DHi. Compared to DHi baseline, the combustion of B7 and B10 reduced the HC emissions by 25.3% and 28.3%, respectively. The presence of oxygen in the biodiesel molecule promotes a more complete combustion and, consequently, lower HC emissions [3].
3.2.2 Carbon monoxide

Carbon monoxide is an incomplete combustion exhaust gas and also depends on other factors such as speed, injection pressure and injection timing, etc.; the key factor is mainly associated with the rich mixture between fuel and air [10]. Figure 4 depicts the time evolution of CO concentration during HWFET with the three fuels tested. In term of CO concentration, the experimental results show similar trends of HC emissions. There are three common spikes of the CO emitted at 190, 310, and 650 s where the engine was suddenly accelerated to higher velocity. At these points, the engine has to be put in more fuel that generates greater fuel-to-air ratios. The maximum CO concentrations for DHi, B7 and B10 are by 0.836, 0.632 and 0.239 %, respectively. On mass basis in the unit of g/km, the accumulative CO emissions during HWFET cycle from the vehicle running on the test fuels are in the order of B10<B7<DHi, similarly to that of the HC release. When comparing to the DHi baseline, the combustion of B7 and B10 reduced the CO emission by 43.3% and 64.0%, respectively. Fueling the engine with B10 at high oxygen content may shift the fuel and air combination toward leaner mixture, and hence lower CO emission.
3.2.3 Nitric oxide

Typically, nitric oxide is formed by the in-cylinder combustion at high temperature and oxygen concentration, following Zeldovich mechanism [10]. Figure 5 shows time evolution of NO concentration during HWFET with the three fuels tested that shows to affect the NO concentration.

![Figure 5. Time evolution of NO concentration during HWFET with the three fuels tested](image)

In Figure 5, the trends of the results of NO concentrations are similar but differ in amount. On mass basis in the unit of g/km, the accumulative NO emission during HWFET cycle from the vehicle running on the test fuels are in the order of B10<B7<DHi, similarly to those of CO and HC emissions. When comparing to the DHi baseline, the combustion of B7 and B10 reduced the NO emission by 6.0% and 16.5%, respectively. Due to higher cetane number of DHi, the ignition delay is shorter compared to the others and, therefore the fraction of injected fuel is burnt in pre-mixed combustion regime. The pre-mixed combustion is associated with higher pressures, pressure gradients and temperatures in the chamber; all of which increase NO formation [11].

3.3. Smoke opacity and particulate matter

Figure 6 shows time evolution of smoke opacity during HWFET for the three fuels tested. There are three common spikes of the smoke emitted at first acceleration, 190, 310, and 650 s where the engine was suddenly accelerated to higher velocity, presumably high load occurrence. At these points, the engine has been supplied by lots of fuel amounts; these fuels may not be completely burned within limited time. The maximum smoke opacity for DHi, B7 and B10 are by 0.73, 0.67 and 0.30 m⁻¹, respectively. On mass basis in the unit of g/km after conversion from the unit of m⁻¹, the accumulative PM emission during HWFET cycle from the vehicle running on the test fuels are in the order of B10<B7<DHi, similarly to those of previous gaseous emissions. Compared to the DHi baseline, the combustion of B7 and B10 lowered the PM emission by 0.38% and 51.0%, respectively. PM formation, caused by high temperature decomposition, mainly takes place in the fuel-rich zone at high temperature and pressure, especially within the core region of each fuel spray. Increasing oxygen concentration in the biodiesel-diesel blended mixture enhances a soot oxidation process. This reduces local fuel-rich regions and limits soot nucleation early in the formation process, thus reducing PM emissions and smoke opacity [12].
Figure 6. Time evolution of smoke opacity during HWFET with the three fuels tested

Figure 7 evidently shows the emissions of particulate matter and nitric oxide from the combustion of DHi, B7 and B10 during HWFET cycle. The B10 combustion confirms the lower PM level than B7 and DHi, respectively. The use of biodiesel for this case of engine with the HWFET cycle seems to simultaneously reduce PM and NO emissions.

Figure 8 shows particle number concentration-size distribution during HWFET cycle. From the combustion of all the fuels tested, the particles show a greater concentration in smaller size for all fuels but differ in concentration amounts. The total particle number concentrations for DHi, B7 and B10 were by 17,552, 16,901 and 38,085 cm\(^{-3}\) respectively. The count mean diameters for DHi, B7 and B10 were by 380, 508 and 430 nm, respectively. In summary, the greater amount of biodiesel blended fuel such as B10 results in higher particle concentration with smaller size compared to DHi.

Figure 7. Particulate matter and nitric oxide emissions
4. Conclusion
This work studies and compares the release of exhaust gases and particulate matter from diesel vehicle tailpipe fueled with B7, B10 and DHi during HWFET cycle. HC, CO, NO and PM were reduced with alternative biodiesel blended fuels, prominently for B10. Although oxygen content in biodiesel partly presented in the blends promotes more complete combustion by reducing these emissions, the combustion temperature dominates NO reduction among oxidizer-rich mixture. Compared to DHi baseline on mass basis, the combustion of B7 and B10 reduced all emissions: by 25.3% and 28.3% for HC, by 43.3% and 64.0% for CO, by 6.0% and 16.5% for NO, and by 0.38% and 51.0% for PM, respectively. The use of biodiesel for this engine running on the HWFET cycle can reduce PM and NO simultaneously. The total particle number concentrations for all fuels are in the range of 16,901 to 38,085 cm\(^{-3}\) while the count mean diameters are in the range of 380 to 508 nm. The greater amount of biodiesel blended fuel such as B10 results in higher particle concentration with smaller size compared to DHi.

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