

## ORIGINAL ARTICLE

# An Analysis of Emissions from An Ethanol Flex-Fuel Vehicle under Two Distinct Driving Cycle Tests during Cold Start

W. Songkitti, T. Aroonsrisopon, and E. Wirojsakunchai\*

Faculty of Mechanical Engineering, Kasetsart University, 50 Ngam Wong Wan Rd, Lat Yao, Chatuchak, Bangkok, 10900, Thailand  
 Phone: +66(0)847561115; Fax: +66(0)25794576

**ABSTRACT** – Ethanol flex-fuel vehicles are introduced to Thailand’s market and believed that they provide an alternative way in terms of reducing crude oil and octane booster import. Many literatures suggested that they also helped to reduce some emission species including the greenhouse gas. However, sufficient proof of this flex-fuel vehicle comparing the conventional versus realistic driving cycle tests during cold starts is not clearly identified. This research focuses on the comparison of performance, fuel consumption, and emissions of a flex-fuel vehicle using Gasohol E10, E50, and E85 tested under the New European Driving Cycle (NEDC) and Bangkok Driving Cycle (BDC). Tests were done on a Chassis Dynamometer in the Automotive Emission Laboratory of the Pollution Control Department. Considering emission data from both test cycles, the more ethanol ratios in gasoline, the more CO, NMHC, NO<sub>x</sub>, CO<sub>2</sub> and PN emissions reductions. On the contrary, HC emissions are increased but still under EURO4 standards. Fuel consumptions on E85 are increased around 30% compared to E10 for both test cycles. However, the pattern of driving cycles significantly impacts the amounts of CO/NO<sub>x</sub> emissions and fuel consumption. During cold start periods, regardless of percentages of ethanol blends, the amounts of HC and CO emissions for both test cycles are similar due to running engine in rich conditions by ECU management to warm three-way catalyst. On the contrary, NO<sub>x</sub> emissions are strongly related to frequent acceleration and deceleration sequences of the tested driving cycle.

## ARTICLE HISTORY

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## KEYWORDS

*Flex-fuel vehicle;*

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## NOMENCLATURE

NEDC	New European Driving Cycle
BDC	Bangkok Driving Cycle
HC	Hydrocarbons
NMHC	Non-methane hydrocarbons
CO	Carbon monoxide
NO <sub>x</sub>	Oxides of nitrogen
CO <sub>2</sub>	Carbon dioxide
PM	Particulate matter
PN	Particulate number
E10	Ethanol content 10% and benzene 90%
E50	Ethanol content 50% and benzene 50%
E85	Ethanol content 85% and benzene 15%

## INTRODUCTION

Air pollution produced by internal combustion engines such as unburned hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), and particulate matter (PM) is a major concern worldwide [1]. In addition, carbon dioxide (CO<sub>2</sub>) emission which is one of the main greenhouse gases (GHG) [2] also becomes increasingly significant aware. For all these reasons, nations worldwide are striving to develop cleaner alternative fuels from renewable sources. Amongst renewable fuels available for the automotive sector, ethanol-gasoline blends (e.g. E10, E20, E85) are recognized as one of the essential alternative fuels for SI engines [3, 4, 5]. The vehicles that are designed to operate on any blends of ethanol to gasoline up to 85% by volume are called flex-fuel vehicles. Most literatures indicated that comparing between E10 and E85 on a flex-fuel vehicle, the amounts of HC, CO, NO<sub>x</sub>, and CO<sub>2</sub> emissions are lower, but fuel consumption is around 30% higher [6, 7]. These are due to changes in fuel’s chemical properties [8, 9], flame speed [10], heat release, and thermal efficiency [11]. Therefore, most engine manufacturers adjusted engine operating conditions to maintain vehicle performance by optimizing vehicle emissions to pass emission standards. However, the pattern of driving cycle strongly impacts the amounts of vehicle emissions and fuel consumption as well [12]. The driving cycle is a time series of vehicle speeds recorded at successive (equally spaced) time points [13]. It represents a typical driving pattern for the population

of a city. For emission testing, a tested driving cycle in the most general case attempts to synthesize real driving conditions with respect to several measures, including speed, acceleration, specific power, trip patterns, road grade, and temperature. In [14], tested emissions of modern ethanol light-duty flex-fuel vehicles over different operating and environmental conditions by variations of ethanol blends and driving cycles were studied. The results of this study were unable to pinpoint which ethanol blends was the best in terms of reducing emissions since the impact of driving cycle pattern also greatly affected emissions. In addition, other studies [15, 16] also show a comparison between tests of flex-fuel vehicles in New European Driving Cycle (NEDC) and World harmonized Light-duty vehicle Test Cycle (WLTC) and the same results were yielded as [14]. Emissions during cold start periods are known that they are relatively high and last approximately within the first three minutes of the test. Once the exhaust temperature is high enough, tail-pipe emissions are much lower. It is hypothesized that this might cause differences seen in past literatures. However, no research has shown and analyzed the emission during this period closely.

The aim of this study is to highlight a comparison of vehicle emissions and fuel consumption of a flex-fuel vehicle testing between Bangkok Driving Cycle (BDC) and New European Driving Cycle (NEDC). Gasohol E10, E50, and E85 are used as tested fuels. Emissions during cold start periods from three tested fuels under two distinct driving cycles are fully analyzed.

## METHODOLOGY

A flex-fuel vehicle under Euro 4 emission standard was used to perform the experiment. The key specifications of the test vehicle are presented in Table 1. The vehicle was regularly serviced according to its manual. Before performing the experiment, the vehicle prepared for each fuel tests (E10, E50, and E85) was filled up in the full tank and driven until the fuel tank was empty for three times. This was done to ensure that the ECU of the vehicle learns each fuel type thoroughly [17]. After that, the vehicle was parked at least six hours before the cold start test began [18]. Ethanol-gasoline blends were prepared by Prakhonng Oil Terminal, PTTOR PLC. Selected important properties are shown in Table 2. The procedure of preparing E50 can be found in Ref. [19].

**Table 1.** Technical specifications of the test vehicle

Properties	Specification
Engine type	4 Cylinder in-line, SOHC 16 valve
Fuel supply system	Electronic fuel injection system
Capacity (cc.)	1,798
Bore x Stroke (mm.)	81.0 x 87.3
Compression ratio	10.6:1
Max. output EEC net kw (ps)/rpm	104 (141) / 6,500
Max. torque EEC net Nm (kg-m)/rpm	174/4300

**Table 2.** Selected properties of ethanol-gasoline blends.

Properties	Gasohol 95 (E10)	Gasohol E50	Gasohol E85
Ethanol Content, % vol.	9.33	50.23	79.58
Research Octane Number (RON)	96.0	>100	>100
Motor Octane Number (MON)	85.0	87.2	88.6
Dry Vapor Pressure (kPa)	58.4	43.7	38.2
Density @ 15°C, Average, g/cm <sup>3</sup>	0.7456	0.7598	0.7807
HHV (MJ/kg)	40.59	35.34	32.12
LHV (MJ/kg)	38.82	33.44	28.72
% of Oxygen Content	9.376	26.734	32.348
Stoichiometric air/fuel ratio	14.1	10.5	9.4

## Vehicle Performance Test

Even though this effort does not include in the scope of this work, vehicle performance tests were performed according to the full-load power test procedure to investigate the impacts of ethanol fuel blends. The test vehicle was warmed up prior to each vehicle performance test. The vehicle was driven at the 5<sup>th</sup> gear on the chassis dynamometer at a constant speed of 80 km/h for 20 minutes. The roller of the chassis dynamometer was controlled at constant speeds from 50 to 140 km/h. Each test lasted for 3 minutes. During 3 minutes of each vehicle speed, the driver pushed the accelerator pedal at full throttle position (engine runs to the maximum speed at 4<sup>th</sup> and 5<sup>th</sup> gear). The powers and torque at each speed were then recorded.

## BDC vs NEDC Driving Cycles

Two driving cycle tests are employed in the current study. The first one is called Bangkok Driving Cycle (BDC) which represents the actual on-road driving pattern found in Bangkok, Thailand. This cycle was developed by the Automotive Emission Laboratory of the Pollution Control Department. The Bangkok driving cycle phase 3-4-5 profile was selected for the current study and shown in Figure 1. In general, the obtained driving cycle lasts 1,456 seconds (24.27 minutes)

whose average velocity is at 33.38 km/hr. More details on the development of the Bangkok driving cycle can be found in the reference [20].

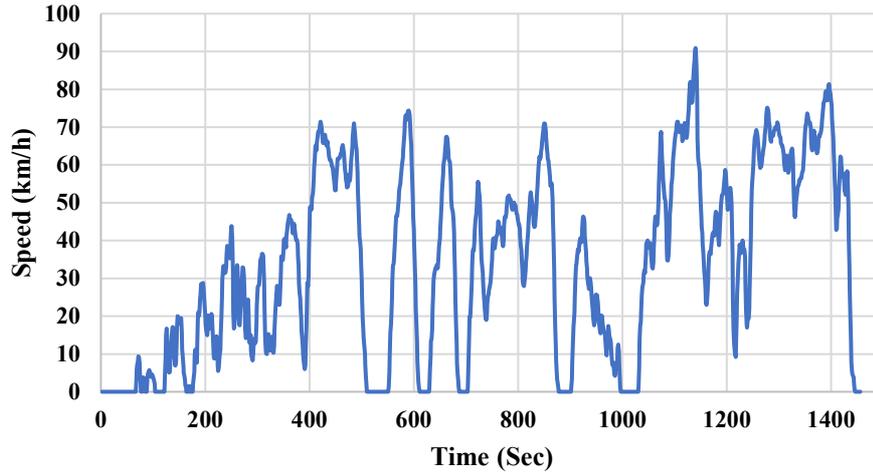


Figure 1. Bangkok Driving Cycle (BDC) phase 3-4-5.

The second one is New European Driving Cycle (NEDC) which is composed of four urban driving sequences (ECE), and an Extra-Urban Driving Sequence (EUDC). This test cycle is the standard test of which many countries including Thailand has currently employed as the legislative driving pattern. The EUDC segment is added after the fourth ECE cycle to account for more aggressive and high-speed driving mode as shown in Figure 2. In general, the obtained driving cycle lasts 1180 second (19.67 minutes) whose average velocity is at 33.4 km/hr.

In general, the duration and average speed of these two driving cycles are similar. However, NEDC is the simpler test pattern since it contains straight acceleration, constant speed, and deceleration profiles which is not reflect real-world driving behavior. BDC, on the contrary, contains more transient speed variations which reflect real-world driving conditions. Another observation is that during the first three minutes of the NEDC test, one ECE sequence is already finished whereas during the same window period, the BDC test is more idle and has low vehicle speed conditions. These two distinct patterns reflect greatly in vehicle emissions which are discussed more in the further section. Table 3 includes a summary of parameters for both ECE and EUDC cycles [12].

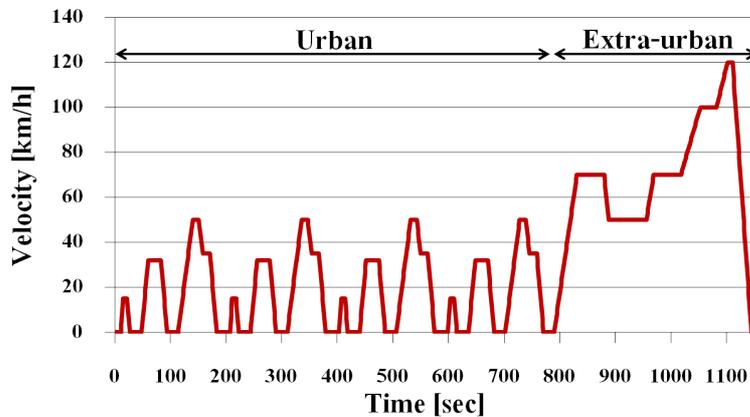


Figure 2. New European Driving Cycle (NEDC).

Table 3. Characteristics of ECE and EUDC driving cycle.

Characteristics	Unit	ECE 15	EUDC
Distance	km	4x1.013 = 4.052	6.955
Duration	s	4x 195 = 780	400
Average Speed	km/hr	18.7 (with idling)	62.6
Maximum Speed	km/hr	50	120

### Sampling and Analytical Systems

The experiments were performed at the Automotive Emission laboratory, Department of Pollution Control, Ministry of Natural Resources and Environment. The laboratory is fully equipped to measure vehicle emissions, fuel consumption, and performance as shown in Figure 3. Surrounding temperature and absolute humidity of air in the laboratory room were maintained at the specified ranges during test periods to avoid any effects on the measurements. The equipment and its technical specifications are described in the following sections.

- i. Chassis dynamometer: consisting of roller and cooling fan.

- ii. Exhaust gas sampling system: collecting samplers for measuring emissions drawn by direct sampler and constant volume sampler (CVS).
- iii. Emissions analyzer: composing of equipment as shown in Table 4.
- iv. Vehicle emission test control system: consisting of control room and driver's aid processor.
- v. Calibration equipment.
- vi. Calibration and operating gas.

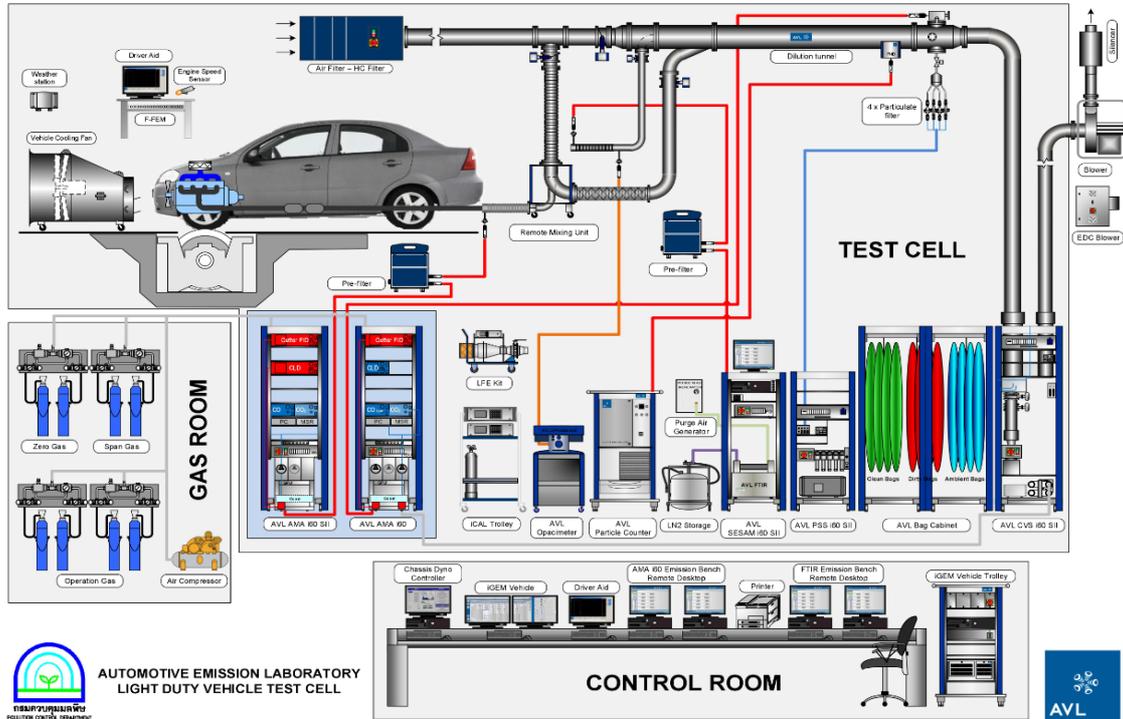


Figure 3. Schematic diagram of the automotive emission laboratory.

Table 4. Emissions measuring equipment.

Measurement	Pollutants	Analyzer
CVS measurement	CO/CO <sub>2</sub>	Non-Dispersive Infrared (NDIR)
	THC (Total HC)	Flame Ionization Detector (FID)
	NO <sub>x</sub>	Chemiluminescence Detector (CLD)
Weighing	Particulate Matter (PM)	Micro Balance

The quantities of each emission species are calculated by Eq. (1) [21]. Fuel consumption (FC) are calculated by Eq. (2) to (4) [22].

$$M_i = \frac{V_{mix} \times Q_i \times k_H \times C_i \times 10^{-3}}{d} \tag{1}$$

where,

- $M_i$  is mass emission of the pollutant 'i' in grams per kilometer,
- $V_{mix}$  is volume of the diluted exhaust gas expressed in liter per test and corrected to standard conditions (273.2 K and 101.33 kPa),
- $Q_i$  is density of the pollutant 'i' in grams per liter at normal temperature and pressure (273.2 K and 101.33 kPa),
- $k_H$  is humidity correction factor used for the calculation of the mass emissions of nitrogen oxides,
- $C_i$  is concentration of the pollutant 'i' in the diluted exhaust gas expressed in ppm and corrected by the amount of the pollutant 'i' contained in the dilution air,
- $d$  is actual distance corresponding to the operating cycle in km.

$$FC \text{ of E10 (liter/100km)} = \left( \frac{0.1202}{\text{Density}} \right) (0.832 \cdot \text{THC} + 0.429 \cdot \text{CO} + 0.273 \cdot \text{CO}_2) \tag{2}$$

$$FC \text{ of E50 (liter/100km)} = \left( \frac{0.1441}{\text{Density}} \right) (0.694 \cdot \text{THC} + 0.429 \cdot \text{CO} + 0.273 \cdot \text{CO}_2) \tag{3}$$

$$FC \text{ of E85 (liter/100km)} = \left( \frac{0.1744}{\text{Density}} \right) (0.573 * \text{THC} + 0.429 * \text{CO} + 0.273 * \text{CO}_2) \tag{4}$$

## RESULTS AND DISCUSSION

### Vehicle Performance

Figure 4 shows test results on the vehicle performance when operating on various ethanol fuel blends at full load condition tests. The result of the vehicle operating on E50 and E85 shows that there is a significant increase in engine performance relative to the baseline E10 when testing in full-load power tests under the engine speed of 3500 rpm. This should benefit from higher octane number leads to more advanced spark timing during low engine speeds. Beyond the engine speed of 3500 rpm, there is no significant difference in terms of engine performance. For full load power tests, E85 provides the best performance which corresponds to reference [23].

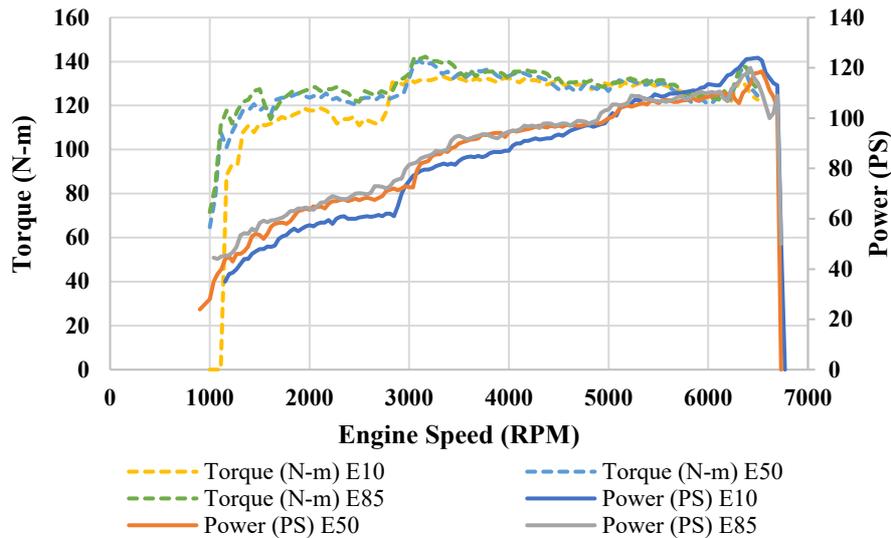


Figure 4. Power and torque curves of the test vehicle at full load conditions.

### Fuel Consumption

Fuel consumption of all test conditions is shown in Figure 5. Within the same driving cycle either BDC or NEDC, E85 yields the lowest fuel consumption with 30% reductions compared to E10 [15]. This is due to its lowest heating value and stoichiometric air/fuel ratio as seen from many suggestions in literatures [6, 7, 9, 22]. However, when comparing each fuel type between two driving cycles, all BDC tests yield lower fuel consumption. This should be because BDC has more sharp acceleration and deceleration sequences than NEDC as seen in Figure 1 and Figure 2.

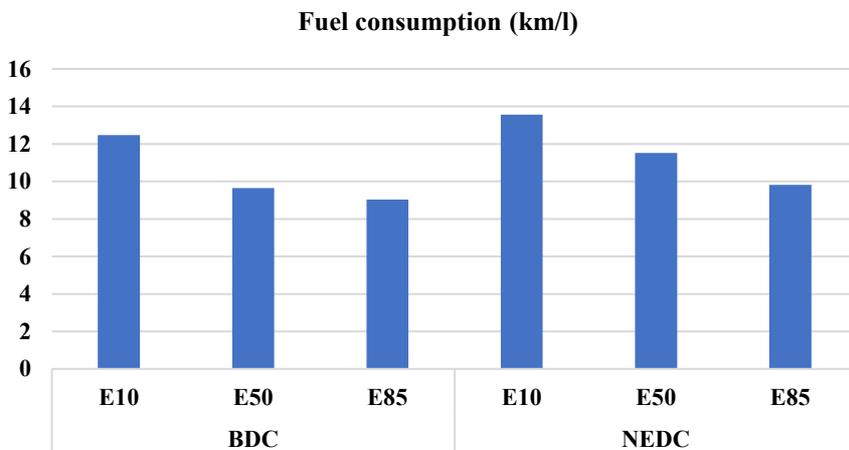
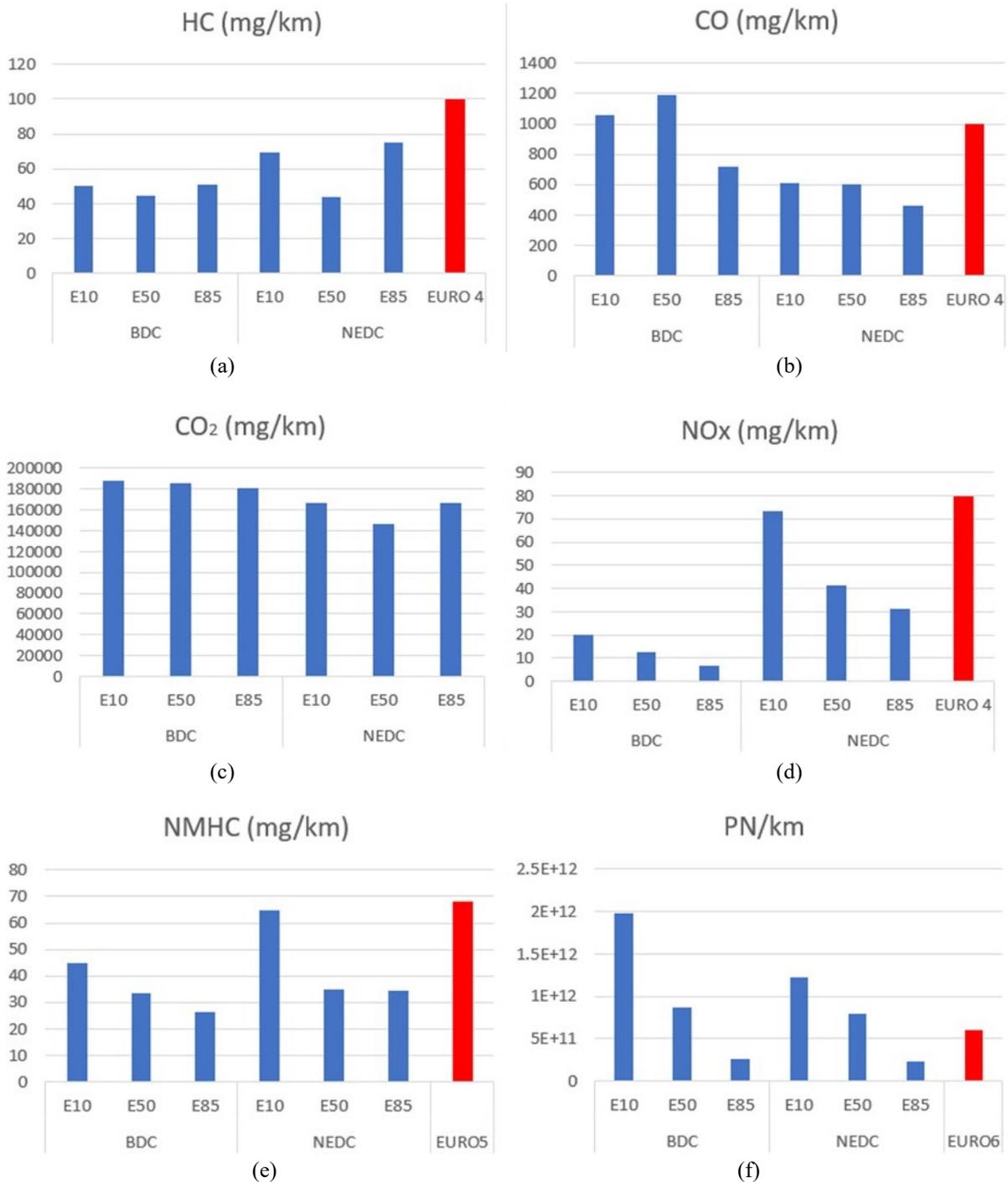


Figure 5. Fuel consumption of the test vehicle under specified driving cycles.

**Effects of Ethanol on Vehicle Emissions under BDC and NEDC Tests**

Vehicle emissions including HC, CO, NO<sub>x</sub>, NMHC, CO<sub>2</sub>, and PN (particle numbers) under BDC and NEDC tests are shown in Figure 6(a) to 6(f), respectively. Results in bar chart formats are compared to EURO 4 emission standards which are the regulated standard for Thailand. Notify that CO<sub>2</sub> is currently not considered as the polluted emission specie in the EURO emissions standard. NMHC and PN are regulated as one of the control emission species since EURO 5 and 6 emission standards, respectively.



**Figure 6.** Emissions data of the tested vehicle operated over the applied driving cycles: (a) HC emissions (b) CO emissions (c) CO<sub>2</sub> emissions (d) NO<sub>x</sub> emissions and (e) NMHC and (f) Particulate number (PN).

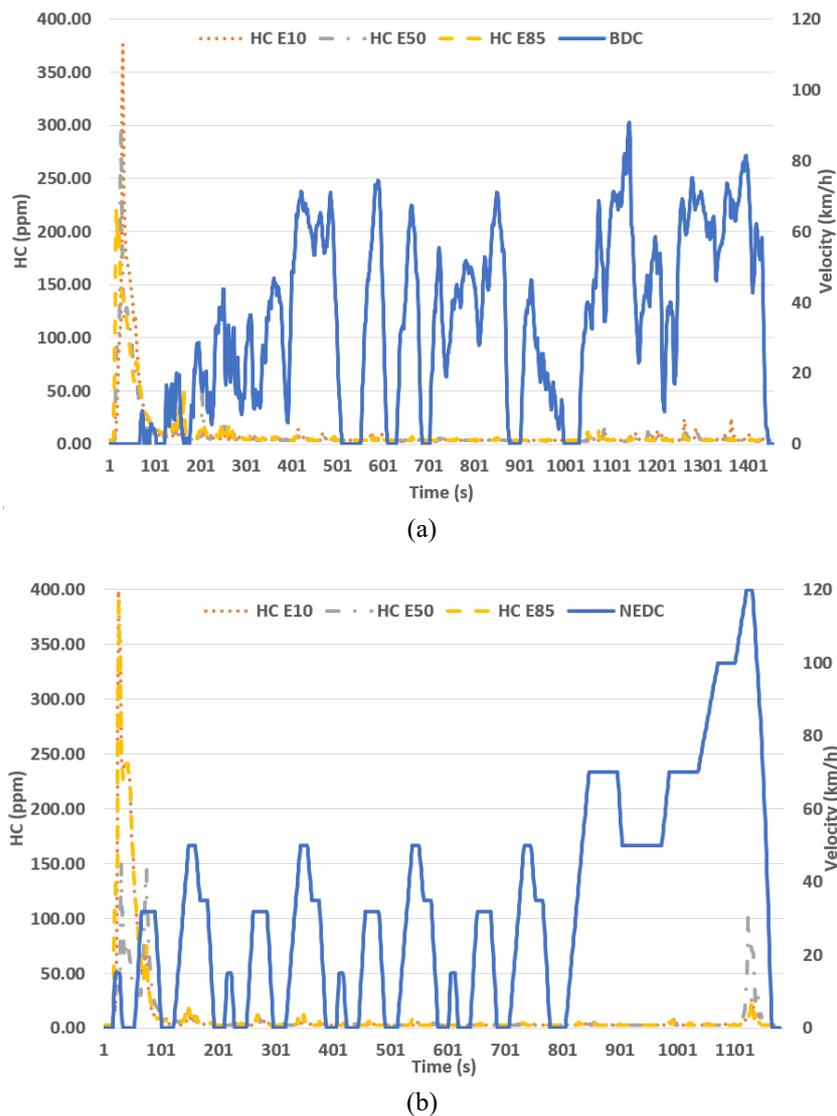
Overall, higher ethanol fuel blends obviously help reducing NO<sub>x</sub>, NMHC, and PN emissions as seen from Figure 6(c), 6(d), and 6(f) for both cycles. These results had been observed in past literature such as [15, 23]. It was speculated that lower heating value of higher ethanol fuel blends should reduce the combustion temperature resulting in lower NO<sub>x</sub> emissions. This trend is not clearly seen in HC and CO emissions (see Figure 6(b)). However, when considering NMHC in Figure 6(c), higher ethanol blends clearly reduce NMHC emissions. More investigations should be done in future work

to identify detailed hydrocarbon emissions with Fourier transform infrared spectroscopy (FTIR) measurements as suggested in [24, 25].

### Effects of Ethanol on Vehicle Emissions under BDC and NEDC Tests during Cold Start

An example of real-time HC emissions data during BDC and NEDC tests are shown in Figure 7(a) and 7(b), respectively. It is clearly seen that HC emissions from both cycles are very high at the beginning and drastically reduced after 200 seconds. This operation window is considered as a cold start period [6] when the operation of a three-way catalytic converter (TWC) is ineffective during this instant of time. The same trends are observed for CO and NO<sub>x</sub> emissions. Table 5 shows the tabulated data of Figure 6 during cold start periods under two specified cycles.

Overall, the amounts of each emission species and fuel consumption in mg/km and km/l, respectively, from BDC are much higher than those from NEDC. This is because during cold start periods, as seen in Figure 7(a) and 7(b), the driving pattern in BDC has much more idling periods than NEDC resulting in less driving distances. Comparisons of each emitted species during cold start periods between two driving cycles will be discussed in the next section.



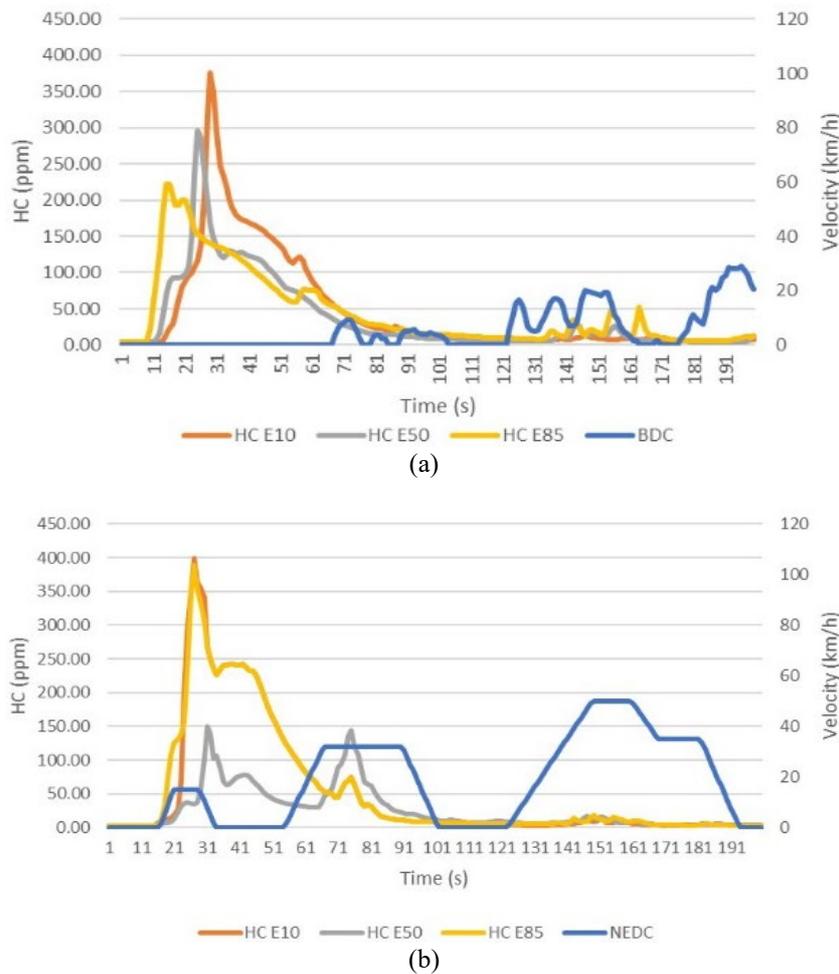
**Figure 7.** The relationship between HC emissions and velocity under (a) BDC and (b) NEDC of each fuel type.

#### HC emissions during cold start periods

Figure 8(a) and 8(b) shows the comparison of HC emissions between both investigated driving cycles during cold start periods. In general, both tests produce similar HC emission patterns even though the driving cycles are significantly different that is BDC has much longer idling conditions than NEDC. HC emissions increase rapidly, and after 80 seconds, reduce significantly. It is believed that running engine in rich conditions by ECU management to warm three-way catalyst should be the cause of these HC emission behaviors, not the driving pattern. When comparing with the same cycle, interestingly, E50 produces less HC emissions than the other two fuel types. This observation should be investigated with various ethanol fuel blends.

**Table 5.** Emissions of the tested vehicle under specified driving cycles during cold start.

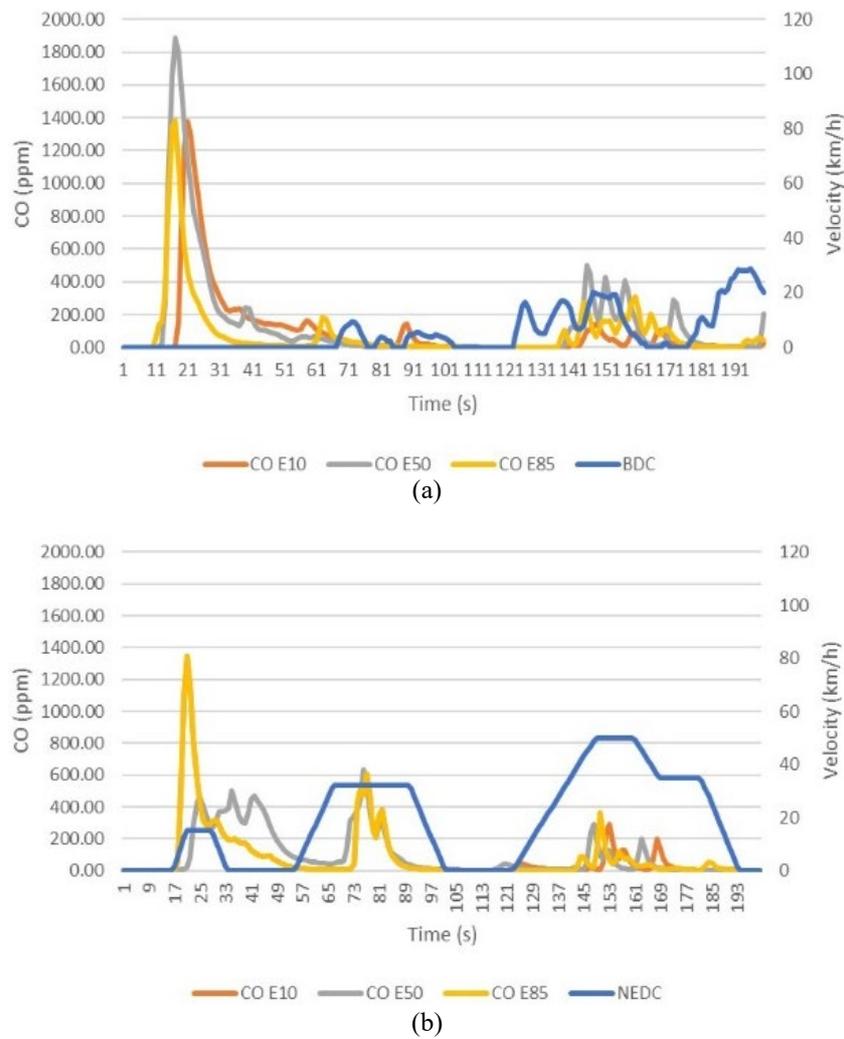
	BDC			NEDC		
	E10	E50	E85	E10	E50	E85
Fuel consumption (km/l)	2.36	1.77	1.74	8.91	8.8	5.11
HC (ppm)	9,121	7,414	8,965	10,743	5,122	10,672
HC (mg/km)	2,790	2,260	2,590	870	410	870
CO (ppm)	18,898	27,442	16,603	17,707	19,147	17,508
CO (mg/km)	11,990	17,050	9,730	2,910	3,110	2,900
NO <sub>x</sub> (ppm)	757	380	201	1,901	1,721	647
NO <sub>x</sub> (mg/km)	800	380	190	540	460	170
CO <sub>2</sub> (ppm)	961,737	1,020,330	998,368	956,822	780,917	1,206,236
CO <sub>2</sub> (mg/km)	934,990	996,550	920,650	247,660	199,870	314,500
PN (#/cm <sup>3</sup> )	3.52E+6	2.86E+6	5.29E+6	1.01E+7	9.49E+6	3.23E+6
PN (#/km)	1.32E+07	1.07E+07	1.87E+07	2.53E+06	3.21E+06	9.54E+06



**Figure 8.** The relationship between HC emissions and velocity under (a) BDC and (b) NEDC of each fuel type during cold start period.

*CO emissions during cold start periods*

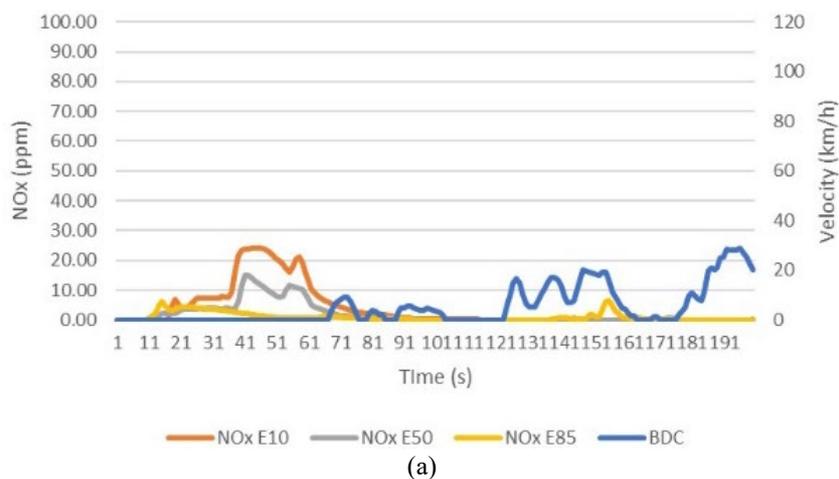
Figure 9(a) and 9(b) show the comparison of CO emissions between both investigated driving cycles during cold start periods. In general, similar trends are observed as seen in HC emissions, that is, CO emissions increase rapidly at the beginning, and after 80 seconds, reduce significantly. BDC tests produce much higher CO emissions in mg/km unit than NEDC tests (Table 5) due to longer idling conditions. Differences in driving patterns of BDC and NEDC do not seem to affect the amount of HC and CO emissions. When comparing within each cycle, E50 produces more CO emissions than the other two fuel types. This observation corresponds to the trend observed in HC emissions.

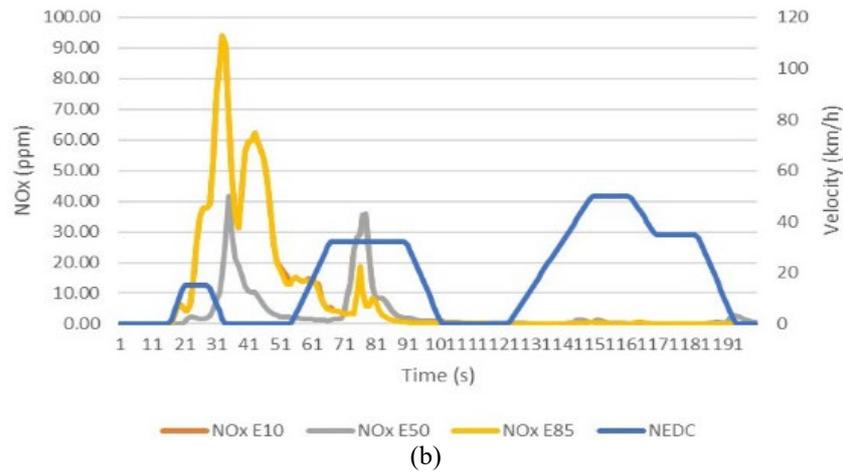


**Figure 9.** The relationship between CO emission and velocity under (a) BDC and (b) NEDC of each fuel type during cold start periods.

*NO<sub>x</sub> emissions during cold start periods*

Figure 10(a) and 10(b) show the behavior of NO<sub>x</sub> emissions between both investigated driving cycles during cold start periods. Interestingly, BDC provides fewer NO<sub>x</sub> emissions than NEDC for all types of fuel during cold start periods. The small appearance of NO<sub>x</sub> emissions during idle periods in BDC compared to a sharp increase during the 1<sup>st</sup> and 2<sup>nd</sup> loop of NEDC indicate that NO<sub>x</sub> emissions are directly proportional to changes in vehicle speeds. The more ethanol blend ratios, the less NO<sub>x</sub> emissions. This is due to the lower temperature of combustion and shorter combustion durations in E85 compared to E50 and E10, respectively [27].

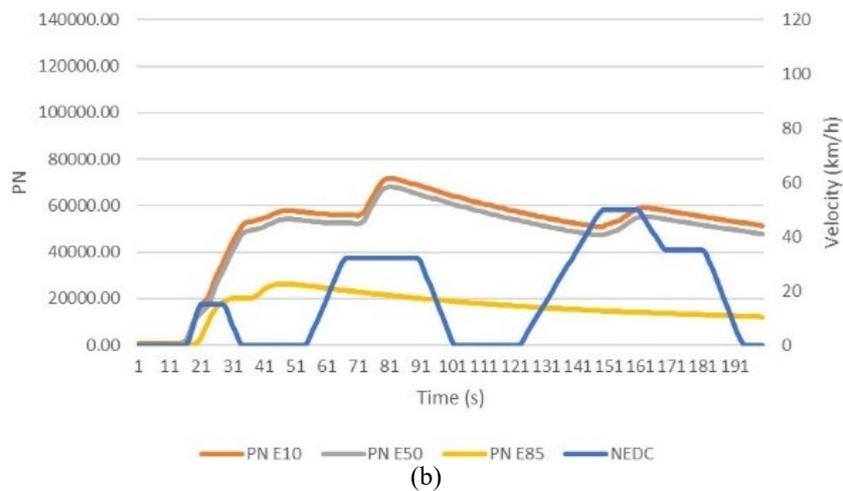
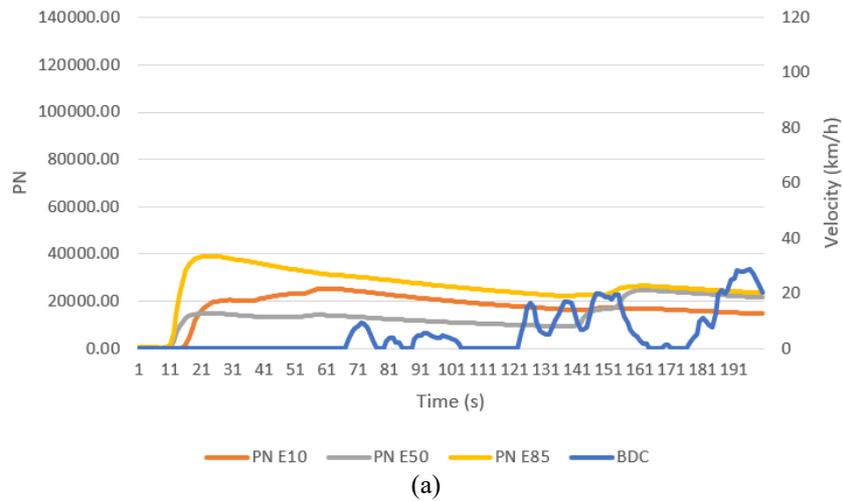




**Figure 10.** The relationship between NO<sub>x</sub> emissions and velocity under (a) BDC and (b) NEDC of each fuel type during cold start periods.

*Particulate number (PN) emissions during cold start periods*

Figure 11(a) and 11(b) show the behavior of PN emissions between both investigated driving cycles during cold start periods. Comparing both cycles, PN emissions are strongly related to the acceleration and deceleration patterns as seen in NO<sub>x</sub> emissions. Since E85 contains higher percentages of oxygen contents than E10 and E50, this should help enhancing oxidization effects resulting in fewer PN emissions [27, 28].



**Figure 11.** The relationship between PN emissions and velocity under (a) BDC and (b) NEDC of each fuel type during cold start periods.

Since BDC is not legally adopted as the regulated procedure on testing vehicle emissions in Thailand, our take on this study is to use it as the other parameter to better understand emissions under cold start periods. We can see that the amounts of HC and CO emissions during this period more likely depends on engine control management regardless of fuel types. However, the amounts of NO<sub>x</sub> and PN emissions are more sensitive to the driving pattern. With higher ethanol blending ratios, these amounts are drastically decreased.

## CONCLUSION

The emissions of a flex-fuel vehicle are investigated under various ethanol fuel blends by performing on two driving cycles, namely, BDC and NEDC. Based on the results found in the current study, the following conclusions are made.

- i. The results from both cycles show that higher ethanol fuel blends help reduce CO, NO<sub>x</sub>, NMHC, and PN emissions. However, HC emissions are substantially higher. This is due to methane emissions from ethanol fuel blends.
- ii. When comparing among same fuel types, more aggressive driving patterns of BDC result in higher CO, CO<sub>2</sub> and PN emissions but HC and NO<sub>x</sub> emissions are reduced.
- iii. Differences in driving patterns of BDC and NEDC and ethanol blend ratios do not affect the amount of HC and CO emissions during cold start periods. The amounts of HC and CO emissions more likely depends on engine control management
- iv. The amounts of NO<sub>x</sub> and PN emissions during cold start periods are directly influenced by acceleration and deceleration sequences in the tested driving cycle. The more changes in the velocities, the more the amount of NO<sub>x</sub> and PN emissions. For both driving cycles, higher ethanol blend ratios help reduce the amount of NO<sub>x</sub> and PN emissions.

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