

Article

Characterization of Emission Factors Concerning Gasoline, LPG, and Diesel Vehicles via Transient Chassis-Dynamometer Tests

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Abstract: Gaseous emissions from vehicles contribute substantially to air pollution and climate change. Vehicular emissions also contain secondary pollutants produced via chemical reactions that occur between the emitted gases and atmospheric air. This study aims at understanding patterns concerning emission of regulated, greenhouse, and precursor gases, which demonstrate potential for secondary aerosol (SA) formation, from vehicles incorporating different engine technologies—multi-point injection (MPI) and gasoline direct injection (GDI)—and using different fuels—gasoline, liquefied petroleum gas (LPG), and diesel. Drive cycles from the National Institute of Environmental Research (NIER) were used in this study. Results obtained from drive cycle tests demonstrate a decline in aggregate gas emissions corresponding to an increase in average vehicle speed. CO₂ accounts for more than 99% of aggregate gaseous emissions. In terms of concentration, CO and NH₃ form predominantly non-CO₂ emissions from gasoline and LPG vehicles, whereas nitrogen oxides (NO_x) and non-methane hydrocarbons (NMHC) dominate diesel-vehicle emissions. A higher percentage of SO₂ is emitted from diesel vehicles compared to their gasoline- and LPG-powered counterparts. EURO-5- and EURO-6-compliant vehicles equipped with diesel particulate filters (DPFs) tend to emit higher amounts of NO₂ compared to EURO-3-compliant vehicles, which are not equipped with DPFs. Vehicles incorporating GDI tend to emit less CO₂ compared to those incorporating MPI, albeit at the expense of increased CO emissions. The authors believe that results reported in this paper concerning regulated and unregulated pollutant-emission monitoring can contribute towards an accurate evaluation of both primary and secondary air-pollution scenarios in Korea.

Keywords: precursor gases; greenhouse gases; LPG; diesel; diesel particulate filters (DPFs)

1. Introduction

In Korea, regulations concerning gaseous-pollutant emissions from vehicles greatly differ based on the type of fuel used. Gasoline- and LPG-powered vehicles follow emission standards of the United

States (US), whereas diesel vehicles comply with European emission-control requirements. NO_x, CO, and non-methane organic gas (NMOG) emissions are regulated in gasoline- and LPG-powered vehicles, whereas that of particulate matter (PM) is exclusively regulated in vehicles incorporating gasoline direct injection (GDI) combustion technology. In diesel vehicles, however, emissions of NO_x, CO, non-methane hydrocarbons (NMHC), PM, and particle number (PN) are all regulated. Furthermore, certain gasoline-, LPG-, and diesel-powered vehicles are subject to additional regulations concerning emission of NH₃ and CH₄ [1], as described in Table 1.

Table 1. Emission standards in Korea(unit: g km^{−1}).

Regulation	Date	CO	NO _x	HC ^a	HC+NO _x	PM	PN	Cycle
Gasoline & LPG ^b								
ULEV	January 2013	1.31	0.044	0.034		0.004 ^c		FTP-75 ^d
ULEV	January 2016	1.31			0.078	0.004		FTP-75 US06 ^e , SC03 ^f
Diesel ^g								
EURO 3	July 2002	1.1	0.95	0.22		0.11		FTP-75
EURO 4	January 2006	0.74	0.39		0.46	0.06		NEDC ^h
EURO 5	September 2009	0.74	0.28		0.35	0.005		NEDC
EURO 6	January 2014	0.5	0.08		0.17	0.0045	6 × 10 ¹¹ km ^{−1}	NEDC

^a Hydrocarbons (HC) content is measured at the tailpipe. HCs are expressed as non-methane organic gas (NMOG) (non-methane hydrocarbons(NMHC) multiplied by 1.04) for gasoline and liquefied petroleum gas (LPG), whereas HCs for diesel are expressed as NMHC. ^b Lightweight vehicles, small and midsize passenger cars, and trucks. Additionally, emission tests performed on used vehicles that are more than 5 years old or have run more than 80,000 km. ^c For vehicles equipped with gasoline direct injection (GDI) engines certified after January 2014. ^d Federal Test Procedure (FTP-75) is defined by the US Environmental Protection Agency (EPA). ^e US06 is a high acceleration aggressive driving cycle. ^f SC03 is the air conditioning cycle under hot ambient condition. ^g Small and midsize passenger cars and trucks. ^h New European Driving Cycle (NEDC). • Remark for gasoline- and LPG-powered vehicles. Large-sized passenger cars and trucks as well as extra-large passenger cars and trucks: NH₃ ≤10 ppm after January 2013. Large-sized passenger cars and trucks as well as extra-large passenger cars and trucks: CH₄ ≤0.5 g/kWh after January 2013. • Remark for diesel-powered vehicles. Large-sized passenger cars and trucks as well as extra-large passenger cars and trucks: NH₃ ≤10 ppm as per EURO 6 certification.

In addition to regulated pollutants, vehicles emit greenhouse gases (GHG) and precursor gases that tend to form secondary pollutants via atmospheric chemical reactions. CO₂—one of the major gases responsible for climate change—accounts for a majority of vehicular emissions. As reported by O'Driscoll et al., CO₂ emission from gasoline vehicles when driving in urban areas increases by 13–66% compared to that from EURO-5- and EURO-6-compliant diesel vehicles equipped with a portable emission-measurement system (PEMS) [2]. Although recent researches demonstrate that direct NO₂ emissions from newer diesel vehicles have been decreased substantially through a more stringent EURO standard, it still constitutes the main reason behind affecting ambient-NO₂ concentration at roadside locations because of high NO_x-emitter diesel vehicles between EURO 3 and EURO 5 standards [3,4] and the fact that NO emissions of some large diesel vehicles have not been decreasing as expected [5,6].

In recent years, the public has become increasingly aware of the production of secondary pollutants via reactions between primary pollutants and other chemicals. In urban areas, vehicular emissions have been found to be a dominant source of gaseous pollutants [7]. Using an oxidation detector inside a confined space, Link et al. investigated secondary-pollutant formation by measuring the production of secondary inorganic aerosols (SIA) from vehicle-emitted NO_x and NH₃ gases [8]. In metropolitan cities, SIA production can be largely attributed to vehicular emissions. Gordon et al. reported that speciated and unspeciated NMOGs contribute towards the formation of secondary organic aerosols (SOA) and that nearly 30% of all NMOGs produced from gasoline in newer vehicles cannot be speciated [9].

Gaseous emissions also result in a variety of environmental issues, including ground-level pollution, climate change (caused by GHGs), and secondary-pollutant formation. Researches concerning gaseous

emissions must, therefore, be more comprehensive instead of focusing exclusively on pollutant emissions. To address this concern, the proposed study measures and analyzes emission trends concerning a wide range of regulated gaseous pollutants, greenhouse gases, and particle-precursor gases released from vehicles fueled with gasoline, LPG, and diesel. Further, gasoline vehicles have been classified based on the engine technology (GDI or multi-point injection (MPI)) incorporated therein, whereas diesel vehicles have been classified based on European emission-regulation standards—namely EURO 3, EURO 5, and EURO 6.

2. Methods

2.1. Vehicle-Selection Criteria and Test Cycle

Table 2 lists the specifications of the vehicles used in this study. High-market-share vehicles were preferentially selected—using data provided by the Transportation Pollution Research Center in the National Institute of Environmental Research (NIER)—and vehicles with similar engine displacements were considered for minimizing differences between emission patterns. To investigate differences between pollutant-emission patterns corresponding to different engine types, gasoline-powered vehicles considered in this study included those incorporating MPI technology, wherein fuel is anteriorly dispersed to the cylinder intake valve, and GDI technology, wherein fuel is directly injected into the cylinder [10]. Vehicles incorporating GDI technology were further classified as pre- and post-PM-emission-regulation vehicles depending on whether they were manufactured prior to or after 2014 (when PM-emission regulations were first imposed on GDI-incorporated vehicles), respectively. PM-emission regulations concerning GDI vehicles influence the combustion technology employed during engine operation. This, in turn, affects the composition of exhaust gases emitted by GDI-incorporated vehicles via hardware and software control to satisfy PM regulation requirements. As already mentioned, diesel vehicles considered in this study were classified in accordance with relevant pollutant-emission regulations, such as the EURO 6 (current regulations), EURO 5 (previous regulations), and EURO 3—which includes vehicles without diesel particulate filters (DPFs) to account for the pollution contribution of older vehicles. EURO-6 compliant vehicles feature three preinstalled after-treatment devices—DPFs, diesel oxidation catalyst (DOCs), and lean NO_x traps (LNTs). Accordingly, EURO-5-compliant vehicles are equipped with DOCs and DPFs, whereas EURO-3-compliant ones exclusively feature DOCs.

Table 2. Specifications of vehicles considered in this study.

No.	ID ^a	Type	Fuel	Year	Displacement (cc)	Engine	Mileage (km)	After-Treatment Device	Emission Standard
1	G1	Passenger	Gasoline	2015	1999	MPI ^b	44,238	TWC ^c	ULEV
2	G2	Passenger	Gasoline	2015	2999	GDI ^d	69,057	TWC	ULEV
3	G3	Passenger	Gasoline	2016	1591	GDI	25,944	TWC	ULEV
4	G4	Passenger	Gasoline	2015	1591	GDI	24,570	TWC	ULEV
5	L1	Passenger	LPG	2014	2999	LPI ^e	87,606	TWC	ULEV
6	L2	Passenger	LPG	2015	1519	LPI	142,492	TWC	ULEV
7	L3	Passenger	LPG	2015	2999	LPI	70,324	TWC	ULEV
8	D1	Truck	Diesel	2016	2497	DI ^f	11,239	DOC ^g , DPF ^h	EURO 5
9	D2	Passenger	Diesel	2016	2199	DI	15,606	DOC, DPF, LNT ⁱ	EURO 6
10	D3	Passenger	Diesel	2016	1582	DI	37,018	DOC, DPF, LNT	EURO 6
11	D4	SUV	Diesel	2002	1991	DI	183,472	DOC	EURO 3

^a Vehicle IDs beginning with G, D, and L indicate gasoline, diesel, and LPG fueling, respectively; ^b MPI: Multi Port Injection; ^c TWC: Three-way Catalyst; ^d GDI: Gasoline Direct Injection; ^e LPI: Liquid Phase Injection; ^f DI: Direct Injection; ^g DOC: Diesel Oxidation Catalyst; ^h DPF: Diesel Particulate Filter; ⁱ LNT: Lean NO_x Trap.

All vehicles were run on a chassis dynamometer in accordance with NIER drive cycle test procedures followed in Korea to measure emissions of GHGs, regulated gases, and SA precursors. The NIER drive cycles have been developed based on Korean road-traffic patterns and comprise 15 different cycles based on the average vehicle speed (from low to high). Drive cycles considered in this study included NIER-01 (average speed: 4.7 km h^{−1}), NIER-05 (average speed: 17.3 km h^{−1}),

NIER-09 (average speed: 34.1 km h^{-1}), and NIER-12 (average speed: 65.4 km h^{-1}) to assess driving conditions within metropolitan cities (Figure 1 and Table 3). Emission measurements during selected chassis-dynamometer tests were performed at ambient temperatures in the range of $20\text{--}27^\circ\text{C}$ and relative humidity of the order of $40\text{--}45\%$ to minimize the effect of variations in the surrounding environment on emissions. Prior to performing measurements, the condition of each test vehicle was evaluated using an On-board Diagnostics (OBD) scanner. Diesel vehicles were evaluated for PM loading within DPFs to assess the need for regeneration. If regeneration was deemed necessary, the same was artificially induced, and gaseous species and particulate matter analyzers were employed to confirm complete regeneration.

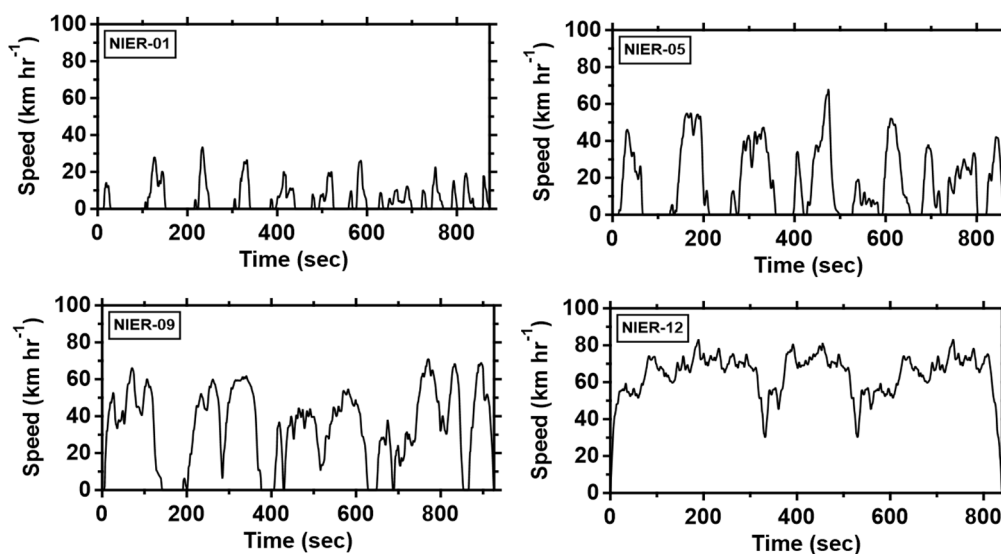


Figure 1. Speed profiles concerning test cycles considered in this study.

Table 3. Specifications of test cycles considered in this study.

Cycle	Total Duration (s)	Distance (km)	Average Speed (km h^{-1})	Maximum Speed (km h^{-1})
NIER ^a -01	873	1.1	4.7	33.4
NIER-05	864	4.2	17.3	68.1
NIER-09	926	8.8	34.1	70.9
NIER-12	840	15.3	65.4	83.3

^a NIER: National Institute of Environmental Research.

2.2. Gaseous-Component Analysis

During chassis-dynamometer tests, exhaust gases from test-vehicle tailpipes were directly sampled using a constant-volume sampler (CVS) tunnel (CVS flow rate: $20 \text{ m}^3 \text{ min}^{-1}$). Gases collected within the CVS tunnel were diluted by the factor of $\sim 10\text{--}95$ using purified dilution air treated by activated carbon and passed through a high-efficiency particle (HEPA) filter. Subsequently, diluted gases within the CVS tunnel were drawn into Tedlar bags, and gas samples were analyzed to determine average concentrations of target pollutant gas species through use of a flame ionization detection analyzer (HORIBA; FIA-720) for total hydrocarbons (THCs), chemiluminescence detection analyzer (HORIBA; CLA-720A) for NO_x , non-dispersive infrared analyzer (HORIBA; AIA-721A and AIA-722) for CO and CO_2 , and gas chromatography flame ionization detection analyzer (HORIBA; GFA-720) for CH_4 . NMHC concentration within exhaust gases sampled from diesel-powered vehicles was defined as THC minus CH_4 , whereas NMOG content within gases sampled from gasoline- and LPG-powered vehicles was defined as 1.04 times the NMHC concentration [1]. After removal of hydrocarbons from gas samples collected from the CVS tunnel, SO_2 concentration within the remaining gas was measured using a pulsed fluorescence detection analyzer (Thermo Scientific; 43C). NH_3 , NO, and NO_2

concentrations were monitored via quantum cascade laser spectroscopy (HORIBA; MEXA-1400QL-NX). NH_3 was directly extracted from the tailpipe using heated tubing (at 115 °C). This is because gaseous NH_3 demonstrates strong adsorption on the walls of the dilution tunnel, thereby inducing errors in measurement of its actual concentration. Measurements concerning NO and NO_2 concentrations within exhaust gas samples were also similarly performed to determine the ratio of NO_2 to NO_x within undiluted vehicle exhaust. Emission rate from CVS tunnel was quantified using Equation (1):

$$\text{Emission rate, g km}^{-1} \text{ from CVS tunnel} = \frac{V_{\text{mix}} \times \rho_i \times C_{i(\text{corrected})}}{d} \quad (1)$$

where V_{mix} is total volume (m^3) in the CVS tunnel during durations of running cycle, ρ_i is the density of gases (kg m^{-3}), and $C_{i(\text{corrected})}$ is the concentration of exhaust gases which is corrected for the CVS tunnel background. d is the total driving distance (km) of each cycle. The direct emission rate was calculated using the following Equation (2):

$$\text{Emission rate, g km}^{-1} \text{ from direct measurement} = \frac{C_{i(\text{corrected})} \times \rho_i \times \text{flow}_{(\text{cvs tunnel})}}{\text{Speed}_{(\text{avg})} \times \text{DF}} \quad (2)$$

where $C_{i(\text{corrected})}$ is the concentration which is corrected by the instrument blank periodically, $\text{flow}_{(\text{cvs tunnel})}$ is the CVS flow rate ($\text{m}^3 \text{ min}^{-1}$) during cycles. $\text{Speed}_{(\text{avg})}$ is the average speed (km h^{-1}) of each cycle, and DF is the dilution factor reported from the measurement of the CVS tunnel system.

3. Results and Discussion

3.1. Characteristics of Gaseous Emissions from Vehicles Powered by Different Fuel Types

Results obtained from chassis dynamometer tests performed as described in the previous section are depicted in Figure 2. A non-DPF-equipped diesel vehicle manufactured prior to the adoption of strengthened pollutant-emission regulations (and hence, considered old) was observed to emit higher concentrations of gaseous pollutants compared to modern vehicles. Except for NO_x emissions from gasoline- and LPG-powered vehicles, the aggregate pollutant emission was observed to decline corresponding to an increase in average vehicle speed. The observed high emission volume during the NIER-01 drive cycle indicates that the functional behavior of after-treatment systems could not be realized until attainment of an appropriate working temperature to facilitate sufficient purification of gas emissions during low-speed operation [11,12].

Investigation of NH_3 emission from vehicles is important from the viewpoint of estimating ambient air pollution in urban areas because gaseous NH_3 can act as a precursor, thereby facilitating SIA production via chemical reactions with NO_x and SO_x [13]. Figure 2f depicts the observed trends concerning NH_3 emission during chassis-dynamometer tests performed at different average speeds. In gasoline- and LPG-powered vehicles, NH_3 emission declines with an increase in average vehicle speed. The corresponding relationship can, therefore, be expressed in terms of an emission factor for calculating the total emission of on-road vehicles. Diesel vehicles, in general, emit low amounts of NH_3 . That said, diesel vehicles equipped with a urea-based selective catalytic reduction (SCR) system tend to encounter a problem referred to as “ammonia slip” emission [14]. Emissions from such vehicles, however, were not investigated in this study. At present, in Korea, NH_3 emissions from large and extra-large passenger cars and trucks are regulated to values not exceeding 10 ppm using the engine driving test [1]. Although results obtained from chassis-dynamometer tests would, in general, differ from those obtained under actual on-road conditions, findings of this study, nonetheless, demonstrate that NH_3 emissions are possible from small- and medium-sized vehicles. Further investigations must be undertaken to determine which vehicles must be subject to additional regulations to prevent the formation of secondary pollutants due to NH_3 emission.

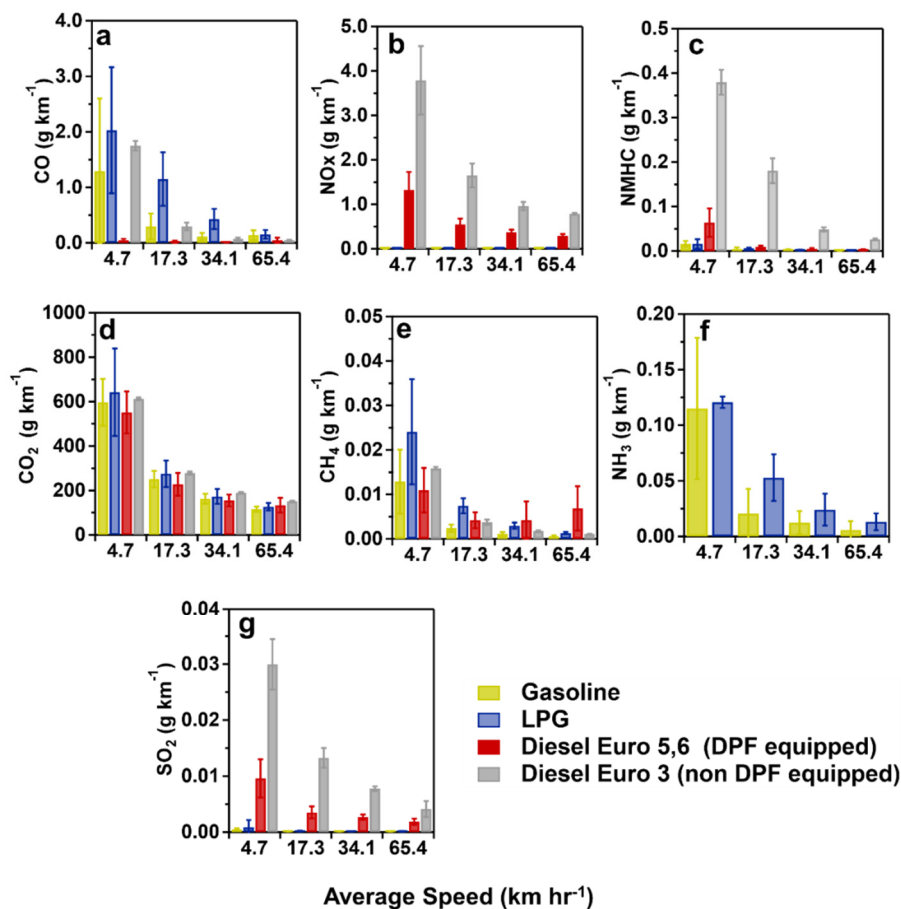


Figure 2. Trends concerning emission rates of (a) CO, (b) NO_x, (c) NMHC, (d) CO₂, (e) CH₄, (f) NH₃, and (g) SO₂ measured during the National Institute of Environmental Research (NIER) cycle tests performed on vehicles powered by different fuels.

Emission of sulfur oxides (SO₂, SO₃, and H₂SO₄) from vehicles is, in general, detrimental to the durability of catalyst devices. Additionally, sulfur oxides react with atmospheric NH₃ to produce ammonium sulfate ((NH₄)₂SO₄)—a secondary pollutant [15]. Most sulfur oxides are produced by the reaction of sulfur present within fuel with oxygen during combustion of fuel–air mixtures within automotive engines. Additionally, a recent study has revealed the conversion of SO₂ to SO₃ within high-temperature after-treatment devices [16]. In Korea, regulations concerning chemical composition of fuels mandate less than 10 ppm of sulfur within gasoline and diesel; the corresponding regulation for LPG mandates less than 40 ppm of sulfur. However, studies concerning actual sulfur-oxide emissions are relatively rare. Figure 2g depicts trends concerning SO₂ emissions when using different fuel types. As observed, SO₂-emission rates vary in the range of 0.0001–0.0005 g km^{−1} for gasoline vehicles, 0.0001–0.0009 g km^{−1} for LPG vehicles, 0.0019–0.0096 g km^{−1} for diesel vehicles, and 0.0041–0.03 g km^{−1} for diesel vehicles without DPF. The high emission rates in diesel vehicles can be attributed to the fact that diesel combustion requires higher air pressures (i.e., greater compression within the engine), which in turn, further enhances the probability of chemical reactions occurring between sulfur and oxygen.

Figure 3a depicts the average pollutant-emission rates calculated during different chassis-dynamometer tests performed in this study. As can be observed, for all fuel types, CO₂—a greenhouse gas—constitutes more than 99% of aggregate emissions, whereas CO constitutes 89% and 92.7% of all non-CO₂ gas species emitted from gasoline- and LPG-powered vehicles, respectively. Corresponding mass fractions for NH₃ were 7.6% and 4.7%, respectively, for gasoline- and LPG-powered vehicles, whereas those for other gases were measured by less than 1%. On the other hand, mass fractions

of emitted NO_x species equal 91.2% and 71.9% in diesel vehicles with and without DPF, respectively. Corresponding mass fractions of CO and NMHC in DPF equipped diesel vehicles are 4.2% and 3%, respectively. Diesel vehicle without DPF emits a significant amount of NO_x while also featuring relatively high CO and NMHC mass fractions (20.8% and 6.5%, respectively). This implies that non-DPF-equipped diesel vehicles release more complex air pollutants compared to vehicles powered by other fuel types. These results demonstrate the importance of classifying test vehicles based on fuel type with regard to calculating the amount of air pollution caused by different fuels. The results also facilitate the imposition of customized regulations on the use of specific fuel types. Most importantly, such regulations would help restrict both the emission of primary pollutants and potential formation of secondary pollutants within the atmosphere. Further investigations in this regard must, therefore, be undertaken.

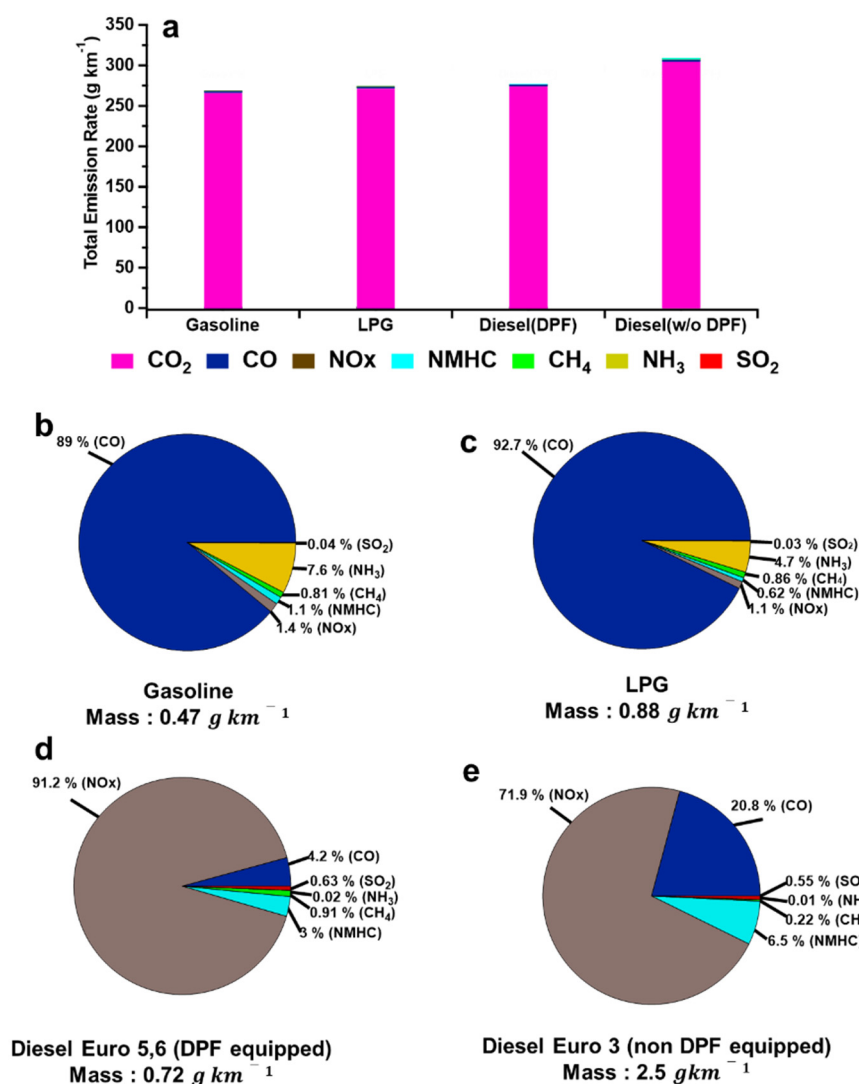


Figure 3. (a) Rates of CO₂ emission of gases constituting different fuels. Mass fractions all gases except CO₂ in (b) gasoline, (c) liquefied petroleum gas (LPG), (d) diesel particulate filter (DPF)-equipped diesel, and (e) non-DPF-equipped diesel. All values correspond to total averages calculated during NIER chassis-dynamometer tests

3.2. Emissions Caused by Use of Different Gasoline-Combustion Technologies

Two types of combustion technologies—MPI and GDI—exist for use in gasoline vehicles. GDI-based vehicles benefit from enhanced fuel efficiency and reduced CO₂ generation compared to

their MPI-based counterparts. However, GDI-based vehicles emit higher amounts of PM compared to those incorporating MPI owing to their inherent incomplete combustion and droplet wall wetting of cylinder surfaces [17]. In 2014, the Korean government imposed regulations on PM emissions from gasoline with GDI engine- and diesel-powered vehicles (previously, only diesel-powered vehicles were regulated). For gasoline-powered vehicles equipped with GDI engines, the specified PM-emission limit was set to 0.004 g km^{-1} [1]. This change in emission regulations led to a change in the composition of exhaust gases emitted from the latest gasoline-powered vehicles. Figure 4 depicts observed emission trends from gasoline-powered vehicles equipped with different combustion systems—MPI, GDI 1 (before PM regulations), and GDI 2 (after PM regulations). As observed and previously discussed, total pollutant emissions were observed to decrease corresponding to an increase in average vehicle speed. Additionally, emission rates of gases other than CO_2 demonstrated a decrease with increasing vehicle speed up to a certain point; this was followed by a subsequent increase thereafter. CO accounted for the majority of non- CO_2 emissions. Vehicles incorporating MPI and GDI 2 technologies demonstrated emissions with NH_3 mass fractions in the range of 2–28% of all non- CO_2 pollutants across all chassis-dynamometer tests. In contrast, GDI-1-equipped vehicles demonstrated very low NH_3 emissions (mass fraction of approximately 0.3% of all non- CO_2 emissions). Given that NH_3 is produced via reactions involving CO, H_2O , and NO inside TWCs [18] its emission rate depends on the vehicle's combustion-system type, after-treatment device technology, driving patterns, and vehicle manufacturer strategy towards emission control.

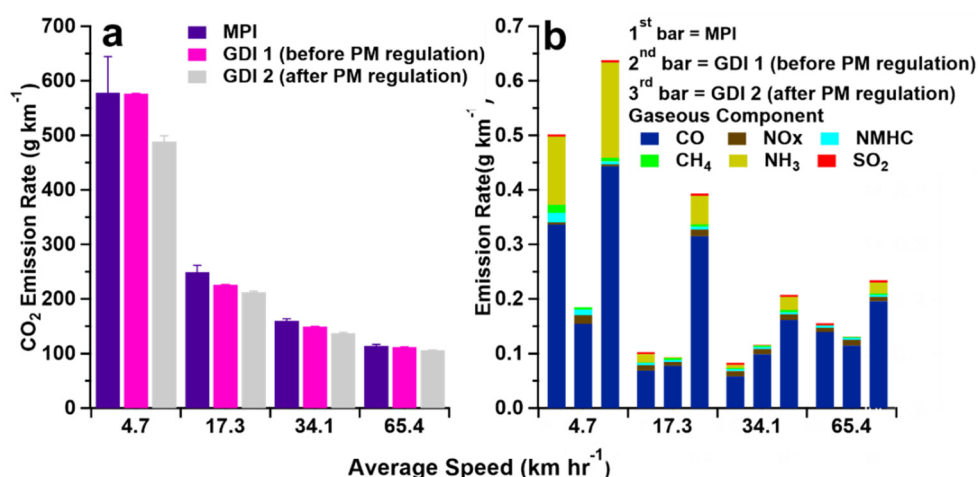


Figure 4. Results obtained from chassis dynamometer tests performed on gasoline vehicles incorporating different combustion technologies and operating at different speeds—(a) Trends concerning CO_2 -emission rate; (b) Trends concerning emission rates of CO, NOx, non-methane hydrocarbons (NMHC), CH_4 , NH_3 , and SO_2

3.3. Emissions from Diesel-Powered Vehicles under Different Emission Regulations

NO_x emissions from diesel-powered engines mostly occur in the form of NO, a portion of which gets further oxidized to form NO_2 within DOCs prior to emission from the tailpipe [19]. Figure 5 depicts emission trends concerning diesel vehicles during the NIER drive-cycle performed in accordance with different emission regulations imposed over time. As can be observed, with the exception of a few measurements, the proportion of NO_2 within NO_x emissions increases with an increase in vehicle speed. However, the magnitudes of these increases are relatively small. In EURO-3-compliant vehicles, NO_2 accounts for only 1–3% of the total NO_x emissions. As regard EURO-6- and EURO-5-compliant vehicles, the corresponding proportions of NO_2 within NO_x emissions lie in the range of 12–16% and 21–28%, respectively. This trend is similar to that reported in extant studies [3,20,21], thereby illustrating the conversion of NO to NO_2 in the presence of a catalyst and high-temperature conditions within after-treatment components.

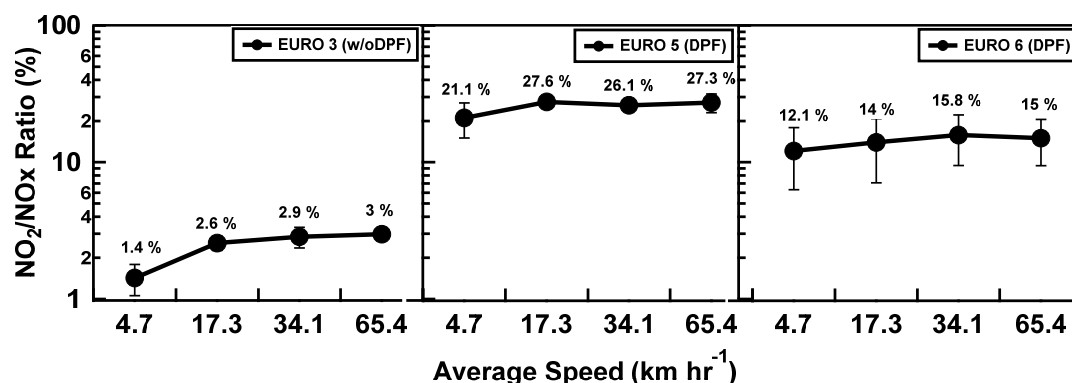


Figure 5. Observed trends in the variation of NO₂/NO_x ratio and standard deviation concerning emissions from diesel vehicles as per different emission-regulation standards for different diesel-vehicle speeds.

EURO-6-compliant emission regulations on diesel vehicles are currently in effect in Korea. EURO 6 features stricter regulations on NO_x and PM emissions compared to EURO [1]. Emissions from diesel vehicles manufactured in accordance with a given regulation standard are controlled via the use of improved combustion technology and after-treatment devices. Figure 6b depicts proportions of regulated, unregulated, and GHG gases within the non-CO₂ emissions from diesel-powered vehicles. CO₂ emissions from EURO-6-compliant vehicles can be observed to be lower as a result of mixed displacement. NO_x, CO, and NMHC are dominant gas species emitted by EURO-3-compliant vehicles without DPFs. NO_x constitutes 89% of the total non-CO₂ emissions from EURO-5- and EURO-6-compliant vehicles. Although emitted concentrations of gas species other than CO₂ have, over the years, been reduced owing to strengthened regulations, the proportions of NO_x emitted from diesel-powered vehicles has remained relatively high. Increased concentration of NO_x gases in the atmosphere may result in the production of hazardous O₃ gas in combination with VOCs (Volatile Organic Compounds) [22,23]. Furthermore, NO_x gases serve as precursor species that react with PMs and other gas species to produce secondary aerosols. Therefore, diesel vehicles that emit large amounts of NO_x gases must be regulated to counter the adverse effects on human health as well as atmospheric pollution.

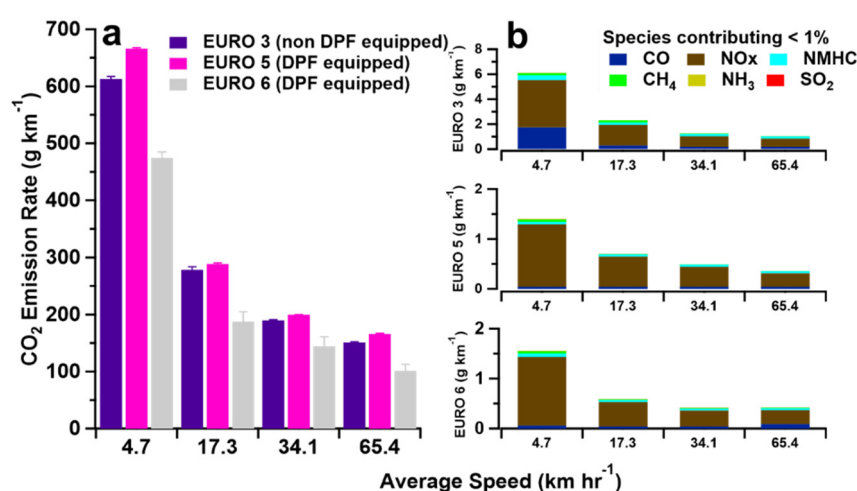


Figure 6. Results obtained from chassis-dynamometer tests performed on diesel vehicles complying with different emission-regulation standards and operating at different speeds. (a) Trends concerning CO₂-emission rates; (b) Trends concerning emission rates of CO, NO_x, NMHC, CH₄, NH₃, and SO₂ gases.

4. Conclusions

This study was performed to investigate and understand the emission patterns of different automotive engines and fuel types used in Korea. Vehicles considered in this study were classified based on their type, the fuel-injection/combustion technology employed, and the emission-regulation standards complied with. Vehicular emissions were detected in real time under conditions of varying average speeds of vehicles. The conclusions drawn from this study can be summarized as follows:

- (1) Emissions of all gaseous pollutants demonstrated an initial decrease with an increase in average speed. For all vehicle types, CO₂ accounted for more than 99% of aggregate emissions, whereas the remaining 1% was comprised of various gas species, and its composition varied depending on the type of fuel used.
- (2) CO and NH₃ were observed to be predominant non-CO₂ species of pollutants emitted from gasoline- and LPG-powered vehicles, whereas emissions from diesel-powered vehicles were dominated by NO_x, CO, and NMHC. Additionally, SO₂ emissions from diesel-powered vehicles were observed to exceed those from their gasoline- and LPG-powered counterparts by up to 28 times.
- (3) Strengthening emission-regulation standards for diesel vehicles has somewhat reduced the effect of NO_x emissions in recent years. However, the value of the NO₂/NO_x ratio has witnessed a significant increase, as depicted in Figure 5, owing to advancement in combustion technology and operating conditions of after-treatment devices.
- (4) Gaseous pollutants, such as NO_x, NMHC, NH₃, and SO₂, emitted by vehicles employing different types of fuel constitute a major source of primary pollution, and these tend to ultimately react with other atmospheric species to produce secondary gases and PM. Inhibition of potential atmospheric pollution, therefore, requires the development of stringent regulations and establishment of emission-reduction policies.

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Conflicts of Interest: The authors declare no conflict of interest.

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