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ASSESSMENT OF HYBRID VEHICLES USING PORTABLE EMISSION MEASUREMENT SYSTEM (PEMS) AS A TRANSITION FOR FULL E-MOBILITY ACHIEVEMENT IN POSITIVE ENERGY DISTRICTS

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Abstract

Air pollution is one of the major concerns, particularly in developing countries, and is a crucial factor in the outbreak of certain illnesses such as cardiovascular and respiratory problems. Moreover, the impact of some pollutants, such as CO_2 as a dominant greenhouse gas, is enormously severe and indisputable on climate and ecosystem conditions. Road transport and mobile sources are considered as the root cause of air pollutants. Some solutions have been implemented progressively to decrease exhaust emissions, such as engine downsizing, alternative fuels, and incorporating novel after-treatment systems. By electrifying the powertrain system, hybrid engines can bring about an efficient fuel economy and fewer exhaust emissions than conventional engines.

Cities are responsible for 80% of the global energy consumption, and with the implementation of zero energy concepts in the larger scales (districts), they can make great strides towards sustainable development. Urban planning schemes must move from mere building solutions to the larger Positive Energy Districts (PEDs) scale. In fact, PEDs, due to their scalability potential, harnessing renewable energy (which sometimes impractical for individual buildings), and achieving a high level of energy efficiency, can be considered advantageous in building decarbonization and promising pathway towards sustainable urban development. Increasing uptake of electro-mobility solutions can play an important role in CO_2 mitigation at the district level.

It is worth noting that measuring the exhaust emissions and fuel economy is undoubtedly important to predict the fleet electrification benefit for the district accurately. Laboratory tests using standard driving cycles under controlled conditions are often criticized for their inability to reflect the vehicle's actual emissions and fuel economy. In other words, the smooth pattern of driving cycles along with the controlled conditions underestimates the real amount of exhaust emissions. Accordingly, Portable Emission Measurement System (PEMS) tests can measure emission factors under real-driving conditions more precisely. In other words, PEMS tests represent real-driving emissions (RDE) which are more realistic and more reliable. In this work, some conventional and hybrid vehicles are considered in terms of their emission factors. In order to understand the emitted level, a comparison between hybrid and conventional gasoline light-duty vehicles using PEMS was made. The results show that hybrid ones are preferable in lower fuel consumption and produce relatively less exhaust emissions. In fact, the conventional group's fuel consumption (CO_2 emissions) was 11 and 41 percent higher than that of hybrid ones.

1.1 INTRODUCTION

Air pollution is one of the major concerns, particularly in developing countries, and is a crucial factor in the outbreak of certain illnesses such as cardiovascular and respiratory problems [1, 2]. World Health Organization (WHO) states that air pollution results in almost 4 million premature deaths each year globally, which underscores the need to utilize novel methods to control and mitigate these emissions. Moreover, the impact of some pollutants, for example, CO_2, on climate and ecosystem conditions is enormously severe and indisputable. CO_2 is dominant amongst GHGs (greenhouse gases). According to International Energy

Agency (IEA) the global amount of CO_2 emissions reached its historic high of 33.1 Gt where the transport section, especially road transport, is responsible for almost one-quarter of total CO_2 emissions, which underlines the importance of mobile sources of air pollution [3, 4]. It should be noted that mobile sources are considered as the root cause of air pollutants. For instance, in the city of Tehran, the Capital of Iran, mobile sources are accounted as the main source of air pollutant emission. According to a recent study, mobile sources are responsible for 85% of the total aggregated pollutants in Tehran, while stationary sources account for the remaining 15% [5].

It is important to note that some solutions are being implemented progressively to decrease exhaust emissions, such as engine downsizing, alternative fuels, and incorporating novel after-treatment systems. By electrifying the power system, hybrid engines can bring about an efficient fuel economy and fewer exhaust emissions. It is accepted that hybrid electric vehicles (HEVs) relatively have higher fuel economy and lower exhaust emissions than conventional internal combustion engine (ICE) vehicles. Moreover, it is envisaged that in 2050 electricity would have a 13% share in supplying needed energy in the transport section [6]. Energy Information Administration (EIA) and IEA report also show an increasing trend and significant sales number of such vehicles in few upcoming years [7, 8].

Cities are responsible for 80% of global energy consumption [9]. The urban area's population is rapidly increased, and it is estimated that almost 66% of the world population will reside in urban parts by 2050 [10]. Cities with the implementation of zero energy concepts on the larger scales (districts) can make great strides towards sustainable development. Urban planning schemes must move from mere building solutions to the larger scale of Positive Energy Districts (PEDs). The district approach allows considering energy interactions between each individual building and the broader energy system at the local level [11]. In fact, PEDs, due to their scalability potential, harnessing renewable energy (which sometimes impractical for individual buildings), and achieving a high level of energy efficiency can be considered advantageous in building decarbonization and promising pathway towards sustainable urban development [9, 10, 12, 13]. Increasing uptake of electro-mobility solutions can play an important role in CO_2 mitigation at the district level. For example, an EU-funded smart city project named POCITYF considers e-mobility integration into smart cities as one solution towards energy management, decarbonization of the mobility sector, and citizen’s mobility costs reduction [9].

It is worth noting that measuring the exhaust emissions and fuel economy is undoubtedly important to have an accurate prediction of the fleet electrification benefit for the district. Laboratory tests using standard driving cycles under controlled conditions are often criticized for their inability to reflect the vehicle's real emissions and fuel economy. In other words, the smooth pattern of driving cycles along with the controlled conditions underestimates the real amount of exhaust emissions. Accordingly, Portable Emission Measurement System (PEMS) tests can be contributing factor in estimating emission factors under real-driving conditions. In other words, PEMS tests represent real-driving emissions (RDE) which are more realistic and more reliable [14].

A few studies dealt with the PEMS measurement of HEVs under RDE-based routes and compared the exhaust emissions and fuel economy with conventional vehicles. Huang et al. [15] compared the exhaust emissions and fuel economy of two pairs of vehicles; each contains one hybrid vehicle (HV) and its conventional vehicle (CV) counterpart. They conducted PEMS tests on three separate routes that included urban, rural, and highway parts. They concluded that HVs had a higher fuel economy than CVs (23%-43% for the first pair and 35%-49% for the second one). The fuel savings were more noticeable in low-speed and urban conditions due to the combustion engine's reducing share. The fuel savings were diminished in highway conditions. Furthermore, both HVs showed considerably higher CO emissions compared to CVs, and their exhaust gas temperatures declined strongly in low-speed parts. This can be attributed to the hybrid system's more start-stop that led to the temperature variation in the three-way catalytic converter (TWC).

Consequently, it impacted the TWC, which reduced the oxidation process. NO_x emissions were lower in HVs. Bielaczyc et al. [16] examined one hybrid and one conventional vehicle's exhaust emissions by utilizing PEMS. The RDE-based test route consisted of a 6 km urban part. The test was performed two times in a similar procedure. The conformity factor (CF) is defined in the article as the ratio of emissions in PEMS test to the applicable limits. HC emissions were low in both vehicles, and CF for HC was <<1. CO emissions were much higher, and CF for the conventional vehicle was about three while CO emissions of the hybrid vehicle were an order of magnitude lower. In addition, NO_x emissions were very low, so that the emission factor of the conventional and hybrid vehicles were 8 mg/km and 2.5 mg/km, respectively. There is a substantial difference between the CO_2 emissions of conventional and hybrid vehicles. Hybrid vehicles mitigated CO_2 emissions by around 55% (132 gr/km vs. 284 gr/km).

Wu et al. [17] explored the exhaust emissions and fuel consumption of two Toyota Prius HEVs using PEMS and compared them with those of conventional gasoline and diesel vehicles. The test route consisted of urban freeways with a total distance of 36km. They incorporated Vehicle Specific Power (VSP) and micro-trip method to inspect and analyze the test results. They found that emissions and fuel consumption almost rose with increasing VSP. Results demonstrated a 27%-40% reduction in fuel consumption of HEVs. Besides, utilizing micro-trip analysis proved that, unlike conventional gasoline vehicles, the CO_2 emissions of HEVs almost insensitive to speed change, so CO_2 emissions decreased by 35%.

In contrast with gasoline vehicles, NOx emissions of HEVs decreased as the average speed diminished. A considerable 90% reduction of NO_x emissions was observed for HEVs. One of the most remarkable outputs of the paper was that the mitigation of emissions, particularly CO_2 and NOx, occurred in low speed and congested traffic conditions. As a result, the authors concluded that HEVs are desired substitutes for conventional gasoline taxi fleets. They also employed economic analysis due to fuel consumption reduction. The results showed that the payback period is about 2~3 years for HEVs. Holmen and Sentof [18] conducted a PEMS test on two Toyota Camry vehicles (one hybrid and one conventional gasoline vehicle). The test route comprised 51.5 km, which included urban, suburban, and highway parts. The authors defined the benefit factor as the ratio between the emission factors of a conventional vehicle to a hybrid vehicle. The benefit factor of HEV CO_2 varied from 0.9 (in higher amounts of VSP) to 6.4 at lower speeds and idle conditions, which indicates the lower emission of HEV at heavy and low-speed traffic conditions.

Additionally, the fuel consumption benefit factor of HEV vehicles were 10, 5, and 2 for city, suburban, and highway conditions, respectively (with the average benefit factor of 2.4 through the entire route). This implies that HEV had better fuel saving at lower VSP and speeds. A tremendous PEMS measurement of 149 diesel, gasoline, and hybrid passenger cars was carried out by O'Driscoll et al. [19]. The vehicles comprised 75 gasoline vehicles and two hybrid ones. The test route consists of 83 km urban and highway parts. Hybrid vehicles played a crucial role in mitigating CO_2 emissions, especially in urban parts. The NO_x emissions of hybrid vehicles were 20 times lower than those of gasoline vehicles. An assessment of emissions of a plug-in hybrid electric vehicle using PEMS was done by Graver et al. [20]. The tests were performed in eight different routes. The results proved that the fuel consumption was roughly 30% lower in charge depleting (CD) than in charge sustaining (CS) mode. Moreover, CD mode reduced CO and NO_x emissions by 25% and 60% compared to CS mode.

In this paper, the exhaust emission behavior and fuel economy of some hybrid and conventional vehicles with various weights and engine volumes are inspected using PEMS measurement in real-driving conditions through four different routes with urban and highway types and flat and uphill slopes.

1.2 MATERIALS AND METHODS

PEMS tests are conducted on the vehicles using Axion OEM-2100 AX portable gas analyzer, as shown in Figure 1. The gas analyzer, powered by a 12V battery, is located at the vehicle's back seat. The sample line collects exhaust gases from the tailpipe and guides them through the filter then the gas analyzer. Portable gas analyzers record the second by second information of O_2, CO, CO_2, HC, and NO_x. The concentration of CO, CO_2, and HC measured by Non-Dispersive Infra-Red (NDIR) and O_2 and NO_x emissions were detected by electrochemical cells. A GPS sensor is connected to the laptop to record vehicle speed along the driving route. OBD II reader device is utilized to log the information of Manifold Absolute Pressure (MAP) and Intake Air Temperature (IAT) on the same laptop necessary for obtaining mass-based EFs.

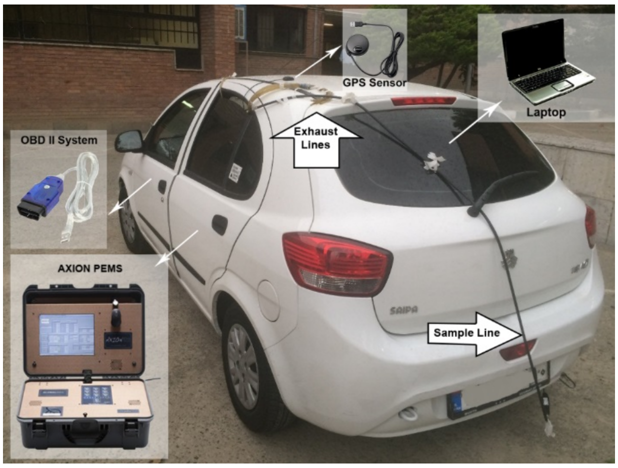


Figure 1. Installation of PEMS main components on the test vehicle

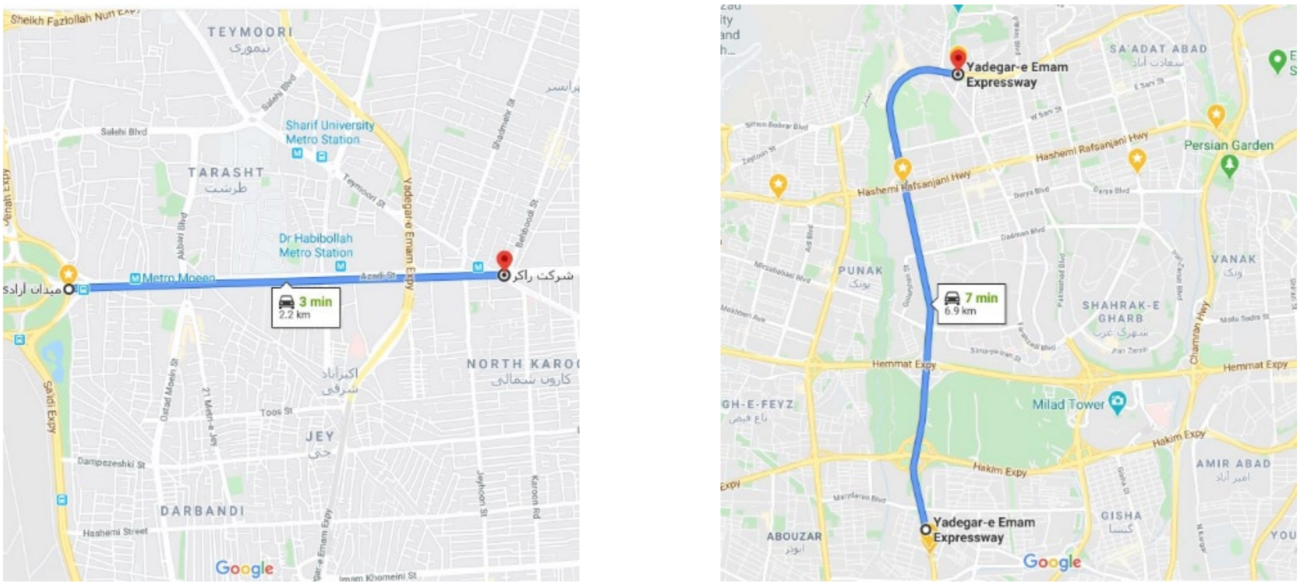
Due to confidentiality reasons, the vehicles' brand is not disclosed. In this study, six spark-ignited, gasoline-fueled conventional vehicles, including CV1 to CV6, are investigated. Also, two different full hybrid vehicles are examined. Hybrid vehicle brand one

(HVB1) contains four identical vehicles with different mileage, including HVB1-1 to HVB1-4. Besides, hybrid vehicle brand two (HVB2) includes two identical vehicles which are different in mileage (HVB2-1 and HVB2-2). The specifications of the six conventional vehicles and two brands of hybrid ones are explained in Table 1.

Table 1. Vehicle Specifications

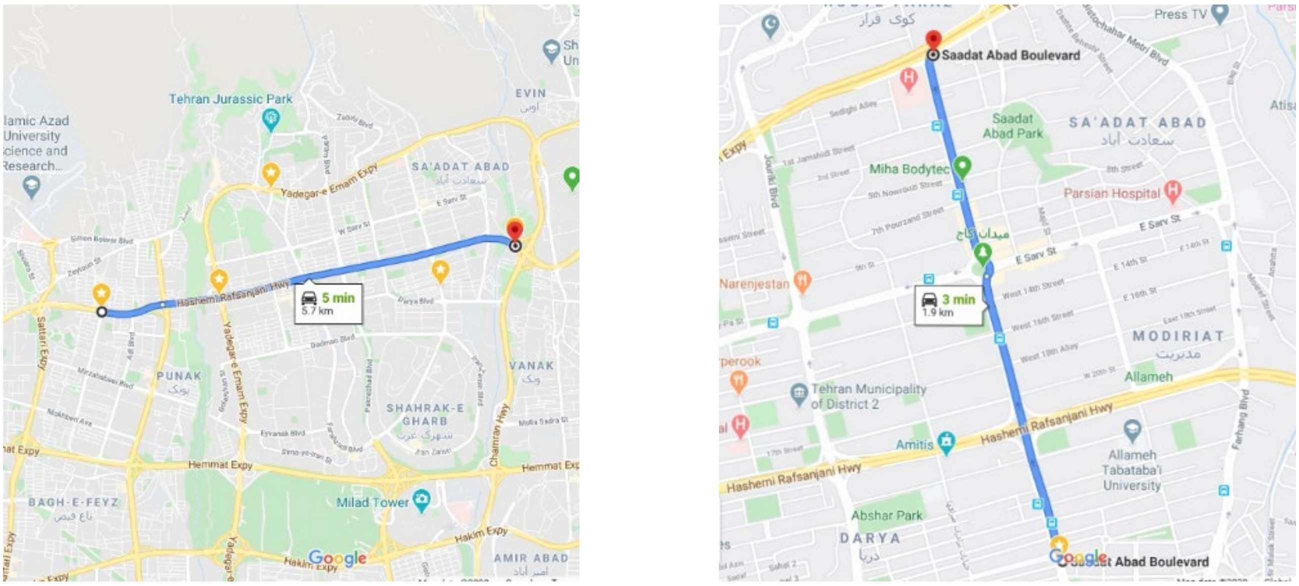
Vehicle	**CV1**	**CV2**	**CV3**	**CV4**	**CV5**	**CV6**	**HVB1**	**HVB2**
Class	Sedan	Sedan	Sedan	Sedan	Sedan	SUV	Sedan	Sedan
Weight [kg]	1258	1755	1471	1460	1332	1760	1580	1383
Mileage [km]	39,970	62,356	51,598	28,445	14,250	30,694	120,000 to 140,000	< 35,000
Engine Volume [L]	1.6	3.3	2.5	2.4	2.0	2.3	2.5	1.8
Max. Power [hp]	115 @ 6000 rpm	293 @ 6400 rpm	178 @ 6000 rpm	185 @ 6000 rpm	150	150 @ 5500 rpm	156 @ 5700 rpm Electric Motor: 140 @ 4500 rpm	121 @ 5200 rpm Electric Motor: 72
Max. Torque [N.m]	157 @ 4500 rpm	346 @ 5200 rpm	230 @ 4000 rpm	241 @ 4000 rpm	192	214 @ 3500	211 @ 4500 Electric Motor: 269 @ 0-1500 rpm	142 @ 3600 Electric Motor: 163

Four different RDE routes were chosen for the PEMS test including urban and highway types with flat and uphill road grades. Figure 2 presents the selected routes on the map and Table 2 summarizes the basic route characteristics.



(a)

(b)



(c) (d)

Figure 2. Selected routes for PEMS test. Source: Google Maps (a) R1, (b) R2, (c) R3, and (d) R4

Table 2. Test routes' characteristics

Route name	Route type	Route length (km)	Road grade (%)
R1	Urban	2.2	0.12 (flat)
R2	Highway	6.9	4.6 (uphill)
R3	Highway	5.7	0.14 (flat)
R4	Urban	1.9	6.9 (uphill)

Each route was repeated three times in each PEMS test. The tests were conducted between 9:00 am and 1:00 pm on different days of a same week in January, 2019. In each PEMS test, the average emission factor and fuel consumption results were calculated by Eq. (1), which uses the weighted average scheme.

$$EF_{overall} = \frac{\sum_{i=1}^{4}(VKT_i \times EF_i)}{\sum_{i=1}^{4} VKT_i} \tag{1}$$

In Eq. (1), *i* is route index, EF_i specifies emission factor (or fuel consumption) of each route, and VKT_i indicates mileage traveled by the i^{th} route. In this study, the routes are chosen in Tehran city, and the percentage of mileage traveled for each one (VKT_i) is obtained from the results of reference [21] because they studied the same routes. VKT_i is equal to 18.3%, 9.9%, 65.2%, and 6.6% for the R1, R2, R3, and R4, respectively.

1.3 RESULTS AND DISCUSSION

The dimensionless fuel consumption and weight are calculated and illustrated in Figure 3 to compare the fuel consumption of conventional and hybrid vehicles. The dimensionless fuel economy is obtained by dividing the fuel economy by 10 L/100 km value. Also, dividing the vehicle weight by 2000 kg gave the dimensionless weight. As seen in Figure 3, the HVB2 has the best fuel economy compared to others. Also, hybrid vehicles have a better fuel economy than conventional vehicles, which is related to stopping the combustion engine in lower velocities and operating points with lower efficiency like idle conditions.

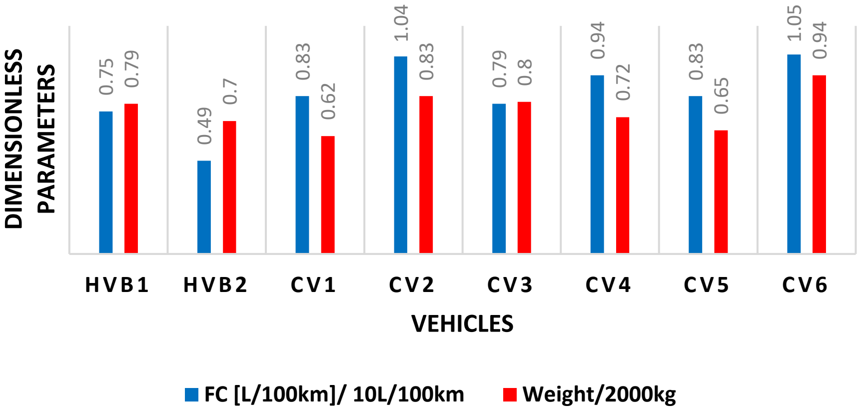


Figure 3. Dimensionless fuel economy (FC) and weight

Also, in Figure 4, the fuel economy of the vehicles in four routes of R1 to R4 is illustrated. The effect of the driving cycle can be seen. In fact, hybrid vehicles' benefit in fuel consumption reduction is much more significant in R1 and R4, urban driving cycles. Since there are several start-stop or acceleration-deceleration in urban driving cycles, it is very beneficial for hybrid vehicles to utilize regenerative braking energy. Most of the time in these cycles, the electric motor is in operation rather than the combustion engine. However, in highway cycles or almost cruising conditions, the differences in fuel consumption with the other non-hybrid vehicles were reduced.

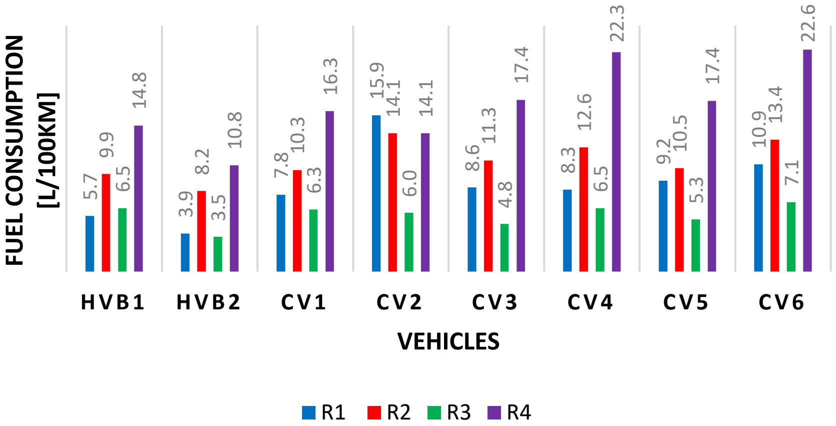


Figure 4. Fuel consumption of the examined vehicles for each route (R1, R2, R3, and R4)

Figure 5 depicts the CO_2 emitted from the vehicles over the four routes in real-world conditions. It is found that HVB1 can mitigate CO_2 by almost 5% to 30% compared to conventional vehicles. This CO_2 mitigation is even more considerable for HVB2, which is 40% to 50%.

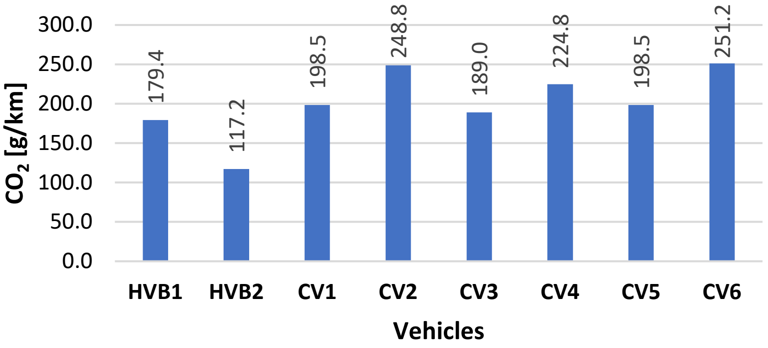


Figure 5. CO_2 emission factor for the examined vehicles

In Figure 6 and Figure 7, it can be seen that hybrid vehicles are complied with the Euro-4 emission standard (0.1 gr/km for HC emissions and 0.08 gr/km for NOx emissions), while CV4 and CV6 exceed NO_x limit, and CV1, CV2, and CV4 do not comply with Euro-4 CO level (1 gr/km for CO emissions). Also, NO_x values for hybrid vehicles are substantially lower (i.e. nine to seventeen times lower) than those of conventional ones.

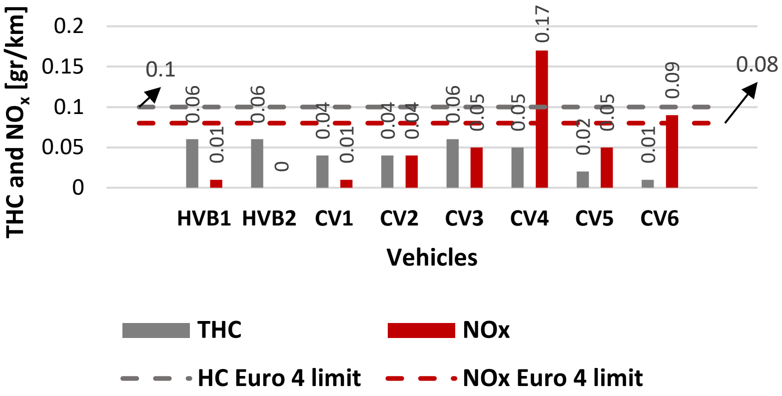


Figure 6. THC and NO_x emissions of the examined vehicles

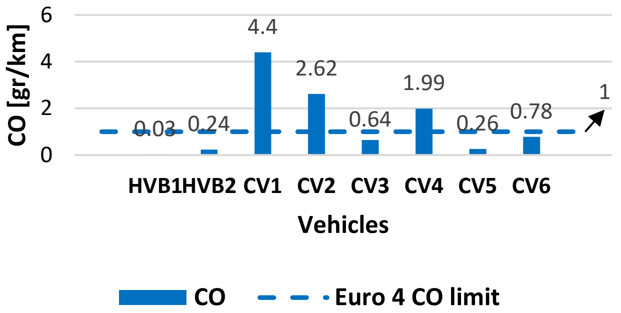


Figure 7. CO emissions of the examined vehicles

1.4 CONCLUSIONS

In this study, two hybrid and six conventional vehicles were inspected using PEMS for their behavior in fuel consumption and emission factors in real-world driving conditions over four different routes. It is found that hybrid vehicles are significantly beneficial in CO_2 and fuel consumption mitigation up to 50%, especially in urban driving cycles, which can be an excellent advantage for utilization in the positive energy districts as a bridge to the e-mobility and battery electric vehicles.

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