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ORIGINAL ARTICLE

Assessment of Static and Extremely Low-Frequency Magnetic Fields in the Electric-Powered Trains

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ABSTRACT
The engine and power supply of trains in advanced rail transit systems are electric (Alternating current (AC) or Direct current (DC)). Such systems generate magnetic fields in the range of static or extremely low frequencies. This study aimed to assess occupational exposure of train drivers to Static Magnetic Field (SMF) and Extremely Low-Frequency Magnetic Field (ELF-MF). This study was conducted in 2014 on intercity and metro trains in Tehran. Seven trains were randomly selected from intercity and metro lines. Based on the BS EN 50500:2008 method recommendations, magnetic fields were measured by the TES-1394 (ELF-MF meter) and HI-3550 (SMF meter). The exposure of drivers was assessed in accordance with of ACGIH-TLVs. The independent sample t-test, Paired samples t-test, one-way ANOVA (with LSD post hoc), and Mann–Whitney nonparametric test were used for data analysis. Mean (±SD) value of ELF-MF and SMF were measured 1.47 (±1.67) µT and <0.1 mT in the intercity AC trains, 0.45 (±0.53) µT and 0.95 (±0.07) mT in the AC trains, and 0.35 (±0.22) µT and 0.08 (±0.86) mT in the DC trains. In addition, maximum exposure to ELF-MF and SMF were 9 µT in intercity AC trains and 1 mT in DC trains, respectively. In none of the situations, exposure of train drivers to ELF-MF and SMF exceeded the ACGIH-TLVs. This does not mean that these magnetic fields are safe and harmless. Hence, the clinical and/or epidemiological study, along with an ELF-MF and SMF exposure assessment of all railway personals, can be helpful for prevention, identification, and treatment of diseases.

KEYWORDS: *Magnetic field, Train driver, Occupational exposure, Iran*

INTRODUCTION
Technological advances of the 20th century, despite the gains made, have led to the 'pollution' of environment and workplaces, in which the modern society exists and develops. The "magnetic field" is the pollution of concern in this study. Magnetic fields may be either static (An electric or magnetic field whose intensity does not vary over time) [1] or alternating with time such as Extremely Low-Frequency Magnetic Field (ELF-MF), cover the range of 30 to 300 Hz [2], and

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workers may expose to these fields in many workplaces such as thermal power plant [3], electric substations [4], and railway specially in drivers [5].

The engine of trains in advanced systems of urban rail transit is electric (alternating current (AC) or direct current (DC)) and the power supply can be electrical, of AC or DC type [6]. Such systems generate Static Magnetic Field (SMF) and ELF-MF [7]. Nowadays, magnetic fields at electrified public transport have been the center of attention.

The average ELF-MF value was measured at 6 mG in electric car and light trunk, 14 mG in jetliner and shuttle tram (AC electrical supply), 20 mG in electric shuttle bus, and 49 mG in commuter train (AC electrical supply) [8]. The average, minimum, and maximum magnetic fields values were reported in different locations of the trains. The maximum values were measured at 3.6 mG in rear floor, 8.7 mG in middle floor, 8.3 mG in front floor, 4.7 mG in driver' seat, and 5.5 mG above the drivers' cabin [6].

The ACGIH and ICNIRP have established Threshold Limit Values for occupational exposure to SMF (Whole body ceiling exposure limit for ACGIH and ICNIRP: 2 T), and ELF-MF (Whole body ceiling exposure limit in 60 Hz for ACGIH and ICNIRP: 1 mT) [2, 9-10]. The level of magnetic fields in electric transport systems is generally less than these threshold limits [7- 8, 11].

However, magnetic field from AC- and DC-powered transport systems may cause a number of adverse human health effects [12-16]. In several Scandinavian studies, the risk of specific types of cancer has increased among railway employees although the total cancer incidence was lower than in general Scandinavian population. There has been an excess of male breast cancer reported among Norwegian Municipal Tram workers [17]. The risk of chronic lymphocytic leukemia was three times greater among engine drivers [18]. The Hazard Ratio (HR) of myeloid leukemia (HR: 1.43; 95% CI 0.74 to 2.77) and Hodgkin's (HR: 3.29; 95% CI 0.69 to 15.63) disease among Swiss railway train drivers was higher than stationmasters [19]. In Addition, some studies confirm the increased risk of sudden cardiac [20] and cardiovascular mortalities [21].

The Tehran Metro: The Tehran Metro is a rapid transit system, using electricity as the motive power, that serving Tehran, the capital of Iran. The Metro consisted of three operational lines, including 1, 2, and 4, and a regional rail line (line 5; Tehran-Karaj). There were three types of trains, including AC and DC metro trains in lines No. 1, 2, and 4 and AC intercity trains in line 5. Both AC and DC trains were being used in all lines, except for line 4 that only the AC trains were being used.

In AC and DC trains, electricity was supplied from a third rail carrying a nominal 750 V DC current. In AC trains, the Inverter by converting 750 V DC to 380 V AC (30-300 Hz), supply electrical power to using in motor, but in DC trains, the current directly used for motor traction. The maximum speed of the AC and DC trains was 80 km/h, but it had limited to 45 km/h due to stoppages at stations along the route.

In the Intercity AC trains, electricity is supplied from 25 kv (50 Hz) overhead lines. The maximum speed of the trains is 140 km/h, but it had limited 80 km/h due to stoppages at stations along the route. This kind of train is used between two cities (Tehran-Karaj), and they are bigger and heavier than AC and DC trains.

In this context, the purpose of the present study was to provide a detailed description on the level of SMF and ELF-MF in Tehran subway system and was to assess occupational exposure level of train drivers to MF. For this, the SMF and ELF-MF were measured in trains and throughout the rail lines. At final step, the exposure of train drivers to SMF and ELF-MF were investigated.

MATERIALS AND METHODS

Study area and measurement tools: This study was conducted in 2014 on intercity and metro trains in Tehran. First, the researchers recorded all available data about the train lines, train types, stations, and schedule of trains, railroad switching places, crossroads, peak-hours, and work schedule of train drivers from Tehran Urban & Suburban Railway Operation Company (TUSROC).

This plan was approved by the Ethics Committee of Tehran University of Medical Sciences, Tehran, Iran. The measurements and entry into cabins were all approved by the Tehran Metro Company.

Three AC (from line No. 1, 2 and 4), 2 DC (from line No. 1 and 2) and 2 Intercity AC trains (from line No. 5) were randomly selected and the trains ID were recorded.

We used a TES-1394 (Electrical Electronic Corp), a triaxial device ELF-MF meter, with a frequency range of 30–2000 Hz. The sampling time of this device was less than one. The TES-1394 contains three orthogonally oriented magnetic field sensor coils (induction coils) [22]. This device is used for measuring magnetic fields up to 200 μT, with a measurement accuracy of ±5%. However, TES-1394 is not suitable for measures SMF. The HI-3550 Magnetic Field Monitor (Holaday Industries, Inc.) was also used to measure SMF. The device contains a Hall Effect Sensor, with three-axis (isotropic) response. The measurement range of HI-3550 was 0.1 to 300 mT, with a measurement accuracy of ±10%. The sampling time of this device was 3 sec.

Before the start of current study, both devices were calibrated by Atomic Energy Organization of Iran, non-ionizing radiation part, and they reported no correlation factor for the devices.

Magnetic flux density measurement: The measurements were conducted with two aims: 1) SMF and ELF-MF at driver's cabin, and 2) Determination of maximum exposure of drivers to ELF-MF and SMF.

In order to assess environmental and exposure levels, the SMF and ELF-MF levels were measured for each train (including 3 AC, 2 DC, and 2 intercity AC trains) in forward/return trips during peak/none-peak hours. When the trains were on the trip, between stations (3 stations), during breaking (3 breaking), during traction (3 tractions), and during railroad switching (2 for each forward and return trip). The measurements were also performed at 4 restrooms and 8 Dispatch Offices. In order to measurement of magnetic fields, 2 researchers and a person who was from the TUSROC, were going to drivers' cabin. All measurements were carried out close to the sources of emission of the trains where workers usually can be in normal operating conditions of train and appliance at the driver seat (about 1 m from the cabin floor, in the nearest point to the driver). The horizontal measuring distance to the walls and appliance was 0.3 m, at least [23]. A researcher was holding the meters in their hands and was reading ELF-MF and SMF, and another researcher was recording the data on paper. For better results, measurements were carried out with three replications, with 3 sec interval (Measurement update period for HI-3550). The minimum, maximum, and average values were recorded for each measurement time. Totally, 1862 measurements were done. This procedure was followed for each randomly selected train in each line. All measurements were done in usual days (there were no holiday or unusual crowded day) including Sundays, Mondays, and Saturdays of Jul 2014.

Driver's exposure assessment: There were about 1200 drivers that worked five days a week, in 3 different shifts (from 5 a.m. to 11 p.m.). Normally shifts' length was 8 h, but they did not work full-time in a shift, and there were two 30-minute breaks. Usually, a train was derived and controlled by a driver in the head cabin.

The cabin is the work environment of drivers, and they were spending about 90% of his working shift's times there (about 7 h). Based on the BS EN 50500:2008 recommendations, measurement of railway environment magnetic field levels with respect to human exposure in a cabin shall be carried out close to the sources of emission of the trains where workers usually can be in normal operating conditions of train and appliance at the driver seat [23]. Sometimes, when the trains had stopped in the stations, and when the drivers of a train were being changed, they were being stood up, and they may have different exposure to MFs, but the current study dismissed these situations.

In addition, magnetic field levels were assessed in Dispatch Office and restrooms. Drivers were spending about 10% of his working shift's times there (about 1 h). However, there was no specific electrical equipment. A TV, which had been showing the traffic of metro, and an amplifier, connected to some speakers in the restroom, were in the dispatch offices, Likewise, a tea maker and a TV were in the restrooms.

According to Threshold Limit Value (TLV) for SMF and ELF-MF recommended by American Conference of Industrial Hygienists (ACGIH), maximum exposure values (ceiling value) should be used for occupational exposure assessment of ELF-MF [2]. Accordingly, in this study, ceiling values of ELF-MF and SMF were used for assessment of train driver's exposure.

Data analysis: Data analyses were conducted using SPSS ver. 14 (Chicago, IL, USA). The independent sample t-test, Paired samples t-test, one-way ANOVA (with LSD post hoc), and Mann–Whitney nonparametric test were used for data analysis. P-values ≤ 0.05 were considered statistically significant.

RESULTS

Train magnetic flux density: Table 1 shows the minimum, maximum, mean, standard deviation (SD) of ELF-MF and SMF in driver cabin. The values in Table 1 were obtained without taking into account the measured values at Dispatch Office and restrooms.

Table 1. Describe Statistical descriptive of ELF-MF and SMF levels in the driver's cabin

Train type	Type of MF	Minimum	Maximum	Mean	±SD
AC trains	ELF (μT)	0.08	5.23	0.45	0.53
	Static (mT)	<0.10	0.35	0.09	0.07
DC trains	ELF (μT)	0.11	1.87	0.35	0.22
	Static (mT)	<0.10	0.52	0.08	0.08
Intercity AC trains	ELF (μT)	0.12	7.90	1.47	1.67
	Static (mT)	<0.10	<0.10	<0.10	<0.10

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Maximum ELF-MF was measured at 7.9 μT in intercity AC trains. Minimum ELF-MF of 1.87 μT was reported from DC trains. Minimum SMF value of <0.1 mT was recorded in intercity AC trains while maximum SMF was measured at 0.52 mT in DC trains.

Table 2 presents a comparison between ELF-MF and SMF values of forward/return trips during peak/ non-peak hours in AC and DC trains.

As Table 2 has shown the SMF in AC trains and ELF-MF in DC trains are significantly different in forward and return trips. There was no significant difference between train weight and values of ELF-MF and SMF.

Table 2. A comparison between ELF-MF and SMF values of forward/return trips during peak/none-peak hours in AC and DC trains

Train type	Type of MF	variable	Mean (±SD)	*P*-value
AC trains	ELF (μT)	Forward trips	0.43(0.32)	>0.05
		Return trips	0.47(0.69)	
		None-peak hours	0.51(0.69)	>0.05
		Peak hours	0.39(0.30)	
	Static (mT)	Forward trips	0.10(0.07)	0.05
		Return trips	0.08(0.07)	
		None-peak hours	0.08(0.06)	>0.05
		Peak hours	0.10(0.08)	
DC trains	ELF (μT)	Forward trips	0.40(0.27)	<0.05
		Return trips	0.30(0.14)	
		None-peak hours	0.36(0.28)	>0.05
		Peak hours	0.34(0.15)	
	Static (mT)	Forward trips	0.07(0.06)	>0.05
		Return trips	0.08(0.10)	
		None-peak hours	0.07(0.10)	>0.05
		Peak hours	0.09(0.06)	
Intercity AC trains	ELF (μT)	Forward trips	1.50(1.70)	>0.05
		Return trips	1.44(1.60)	
		None-peak hours	1.27(1.60)	>0.05
		Peak hours	1.67(1.70)	

Table 3 has shown a comparison between ELF-MF and SMF of trains in different lines. These results were calculated by involving the magnetic fields values of Dispatch Office and restrooms. There were significantly differences between ELF-MF and SMF in Line 5 and other lines (P<0.01), but no significant differences were seen between other lines, excepted SMF in line 2 and 4 (P<0.05). The LSD post hoc test results were showed that there was significant difference (P<0.01) between ELF-MF values of intercity AC trains (mean 1.47; SD: 1.67 μT) and 2 other type of trains (mean: 0.45; SD: 0.54 μT for AC, and mean: 0.35; SD: 0.22 μT for DC).

Moreover, the result of Mann–Whitney nonparametric test showed no significant difference (P>0.05) between the SMF values of AC and DC trains.

Table 3. A comparison between ELF-MF (μT) and SMF (mT) of trains in different lines

Line number	Line 1		Line 2		Line 4		Line 5	
	ELF-MF	SMF	ELF-MF	SMF	ELF-MF	SMF	ELF-MF	SMF
Mean(±SD)	0.38 (0.51)	0.07 (0.07)	0.33 (0.26)	0.06 (0.08)	0.37 (0.40)	0.08 (0.08)	1.20 (1.57)	<0.10
Line 1	-	-	>0.05	>0.05	>0.05	>0.05	<0.01	<0.01
Line 2	-	-	-	-	>0.05	<0.05	<0.01	<0.01
Line 4	-	-	-	-	-	-	<0.01	<0.01

Exposure assessment: The assessment results of driver's exposure to ELF-MF and SMF in different lines are presented in Table 4.

According to Table 4, minimum (0.01 μT), and maximum (9 μT) exposure to ELF-MF were reported among drivers of intercity trains. Minimum (<0.1 mT) and maximum (1mT) exposure to SMF were found among drivers of intercity trains in line 5 and DC trains in line 2, respectively. In the current study, the SMF and ELF-MF levels were measured for AC, DC and intercity AC trains in forward/return trips during peak/none-peak hours, when the trains were on the trip, between stations, during breaking, during traction, and during railroad switching. In addition, occupational exposure of train drivers at Tehran subway to ELF-MF and SMF was assessed as well.

In the current study, the SMF and ELF-MF levels were measured for AC, DC and intercity AC trains in forward/return trips during peak/none-peak hours, when the trains were on the trip, between stations, during breaking, during traction, and during railroad switching. In addition, occupational exposure of train drivers at Tehran subway to ELF-MF and SMF was assessed as well.

Table 4. Minimum, maximum of driver's exposure to ELF-MF and SMF

Line No.	**Train type**	**ELF-MF**		**Static**	
		Min (µT)	Max (µT)	Min (mT)	Max (mT)
Line 1	AC trains	0.08	5.40	<0.10	0.35
	DC trains	0.10	0.80	<0.10	0.31
Line 2	AC trains	0.10	2	<0.10	0.34
	DC trains	0.10	2.80	<0.10	1
Line 4	AC trains	0.08	4	<0.10	0.40
Line 5	Intercity AC trains	0.01	9	<0.10	<0.10

In the current study, the SMF and ELF-MF levels were measured for AC, DC and intercity AC trains in forward/return trips during peak/none-peak hours, when the trains were on the trip, between stations, during breaking, during traction, and during railroad switching. In addition, occupational exposure of train drivers at Tehran subway to ELF-MF and SMF was assessed as well.

Although the ELF-MF and SMF values measured in the current research are close to those of similar studies [7]. However, there are some studies with different reports of ELF-MF and SMF levels, conducted with different methods and tools [7, 24]. These differences may arise from different type of locomotive engines and technologies such as place of engines and energy consumption, power supplies and related conditions such as the distance of overhead line to driver seat or measurement spots, and environmental conditions such as slope of railway. Table 5 provides a comparison of magnetic field levels at trains in previously published studies.

Although reported SMF values in previous studies were partly close to each other, reported ELF-MF values were not. The results of SMF values of current study were close to reported SMF value in Table 5.

Table 5. Results of four studies on magnetic flux density at trains

Researcher(s)	Train type		Exposure level
Nakagava and Koana, 1993[24]	AC train		AMF: 2-1500 mG (0.20-150 µT)
			SMF: 1-40 G (0.10-4 mT)
	DC train		AMF: 5-50 mG (0.50-5 µT)
			SMF: .5-2 G (0.05-.2 mT)
Stavroulakis, 2003[25]	AC train		AMF:0 to 50 Hz- : 0–350 mG (0-35 µT)
Chadwick and Lowes, 1998[11]	750 V DC sub urban railway	AMF	Inside table height: 160–640 mG (16-64 µT)
			Platform: 160–480 mG (16-48 µT)
Contessa et al. 2010[7]	AC trains	AMF (max)	Driver's position at train E: 9.30 µT
			Driver's position at train F: 5.46 µT
		SMF (max)	Driver's position at train E: 100 µT (0.10 mT)
			Driver's position at train F: 120 µT (0.12 mT)
	DC trains	AMF (max)	Driver's position at train A: 20 µT
			Driver's position at train B: 4 µT
		SMF (max)	Driver's position at train A: 80 µT (0.08 mT)
			Driver's position at train B: 160 µT (0.16 mT)

DISCUSSION

Previous studies reported magnetic fields in the different frequencies and train types, but they did not compare these variables by statistic tests, so that, the difference of magnetic fields in the different type of trains was not clearly reported or explain. In addition, all measurement points in the current study were critical, because in those times, magnetic fields might change to the higher or lower levels. However, in some studies, magnetic fields have been monitored in the full time of a trip [7].

Difference of magnetic fields between intercity AC trains (ELF-MF: 7.9 µT max; SMF:<0.1 mT min) and in-city trains (ELF-MF:

1.87 μT min; SMF: 0.52 mT max) may be due to the type of engines, type of locomotive powers (overhead power lines instead of third rail), and the speed difference between two type of in-city and intercity trains that leads to the difference in energy consumption [26]. The intercity trains had a cabin; about 1.5 m behind of drivers, and engine of locomotive was there. In addition, the 25 kv overhead power lines were directly over the cabin, with about two-meter interval. However, the DC trains were supplied by a third rail carrying a nominal 750 V DC current, and there was no engine on any sides of driver cabin. The DC trains engines were under the other trailers of train. However, there was an engine under AC trains.

The results of current study showed that ELF-MF in the AC trains was higher than of DC trains. In addition, the DC trains showed higher values of SMF compared to the AC trains. The AC trains had higher levels of alternative magnetic field (AMF) rather than the DC trains (Table 5). Moreover, another study reported same results. In the driver's position, AMF of the AC trains was higher than the DC trains, and SMF of the DC trains was higher than the AC trains.

In the AC and DC trains, there was significant difference between MF of forward and return trips (Table 2), and this may be due to fluctuations in the electrical current. In addition, in forward trip, there was a mild slope in line 2 (not all trip, some stations only) and 4 that may affect ELF-MF and SMF of AC and DC trains. Additionally,) a complex MFs pattern in electric vehicles was highly variable with time due to changes in route conditions such as slopes and turning [24].

In overall, the exposure level of train workers to the magnetic fields is less than in other occupations such electrical engineering [27-29] or MRI operators [30, 31]. This may be a reason for the lower number of epidemiological studies on harmful effects caused by the magnetic fields on train drivers of different countries in compare with other occupations such as electric power installers and repairers or power plant operators. The results seem to be compatible with the evidence of the laboratory studies on the biological effects of the ELF-MF and SMF [32].

Maximum exposure of train drivers to ELF-MF was 9 μT reported from intercity AC trains. Minimum (<0.1 mT) and maximum (1 mT) exposure to SMF were related to the drivers at intercity (line 5) and urban (line 2) AC trains, respectively. The ELF-MF and SMF values of the Tehran subway are far less than the threshold limits recommended by the ACGIH. This is consistent with results of similar studies [7, 11, 33]. Although based on the ACGIH and ICNIRP threshold limits, exposure of the TUSROCs' drivers was not considerable; there are some health problems in the railway employees exposed to low levels of ELF-MF and SMF. An exposure–response association was found for myeloid leukaemia and Hodgkin's disease in the Shunting yard engineers and train drivers who had medium (average exposure was approximately 6 μT) and high exposure (average exposure was approximately 21 μT) to ELF-MF. However, lymphoid leukaemia, non-Hodgkin's disease, and brain tumor mortality were not associated with magnetic fields exposure [19]. Moreover, exposure of railway employees to ELF-MF (13.4 to 25.9 μT) could increase the mortality rate of leukemia, and brain tumor [32]. The health problems may arise in railway employees, because of exposure to low levels of MF (about 2% of ACGIH threshold limit for MF in the frequency of 60 Hz), and these important results showed that the TUSROCs' drivers can be at risk of some health problems such as myeloid leukaemia and Hodgkin's disease.

There were some limitations in the current study. Since the lower band of the HI-3550 Magnetic Field Monitor is set on 0.1mT, so the measured value at some measurement spots with low level of magnetic fields was zero. In addition, by using some instruments that can measure and record MF over the time, such as Standard EMDEX II, assessment of drivers will be more comprehensive. Moreover, because of some limitations in the TUSROC, little information was available about trains' engines systems, and distance of different station from each other, and, entering into the driver cabin was limit. In intercity AC trains, there was a cabin; about 1.5 m behind of drivers, and engine of locomotive was there. Based on the drivers' state, sometimes, they were being gone to the cabin for repairing purposes; therefore, they had exposure to unknown value of MF. However, the drivers did not let us to entering the cabin.

The present study was showed that different type of AC trains (in-city and intercity) can radiate more ELF-MF and less SMF rather than the DC trains. Moreover, the trains, supplied by overhead lines, can radiate more ELF-MF and rather than the trains, supplied by third rail, therefore, they have more occupational and environmental hazards. In addition, if the in-city trains' engine will not be embedding under drivers' cabin, exposure to MF will be limited.

CONCLUSION

In none of the situations, exposure of train drivers to ELF-MF and SMF exceeded the threshold limits recommended by the ACGIH. This does not mean that these magnetic fields are safe and harmless whereas there is some research on diseases such as leukemia and Hodgkin's disease among workers in the transportation system exposed to low levels of the magnetic. Since, the age of Tehran Metro is about 20 yr, a clinical and/or epidemiological study, along with an ELF-MF and SMF exposure assessment of all railway personals, can be helpful for prevention, identification and treatment of diseases that may be are results of the occupational exposure to ELF-MF and SMF.

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