Emission Rates of Gaseous Pollutants from Motor Vehicles

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Abstract

This study aimed at calculating emission rates of gaseous pollutants from gasoline fueled motor vehicles. Data were obtained from the Jordanian Ministry of Environment, Department of Driving and Vehicles Licensing at Marka, Amman and from a private smog check station in Irbid. Our findings indicate that measured concentrations of gaseous tailpipe pollutants are within the Jordanian standards. Average concentrations of carbon monoxide, carbon dioxide, hydrocarbons, and nitrogen oxides are 3.12%, 11.21%, 398.92 ppm, and 88.78ppm, respectively. Average emission rates are found to be 33.9, 198.4, 1.0, and 0.1 gram per kilometer traveled for carbon monoxide, carbon dioxide, hydrocarbons, and nitrogen oxides, respectively with an estimated uncertainty of ±10%. Emission rates are found to be dependent on many factors including year of manufacture, engine capacity, and fuel type. New vehicles and vehicles with low engine capacity are cleaner than old vehicles and vehicles with high engine capacity.

Keywords: Urban air pollution; Carbon oxides; Nitrogen oxides; Sulfur oxides; Hydrocarbons; Emission rates.

Introduction

Air pollution has been an active area of research due to its adverse health impact[1-4]. High levels of air pollution could cause severe health problems including acute respiratory diseases and allergies[5]. In addition to its adverse health impact, air pollution has negative impacts on animals, vegetation, crops, materials, visibility reduction, and climate change[5].

The impact of motor vehicles on air quality has become an important issue because of the rapid increase in the number of vehicles in use due to the increase in the world population. Estimates indicate that there are 834 million cars[6] serving 6.5 billion people around the world[7]. Those vehicles burn millions of gallons of fossil fuel, which will end up being air pollutants. There are large numbers of substances emitted from vehicles that are capable of causing adverse health effects[5]. In addition, motor vehicles are the largest source of greenhouse gases. About 15% of the world's emissions of carbon dioxide, the principal global warming gas, are generated by motor

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vehicles, which are also responsible for approximately 50% of the emissions of nitrogen oxides worldwide[8]. Motor vehicles generate pollutants through fueling, fuel combustion, evaporation of lubricant, brake-wear, tire-wear and re-suspension of road dust[9,10].

Motor vehicles are the only available transportation mean in Jordan. The number of motor vehicles in Jordan has increased from 31,850,0 vehicle in 1998 to 67,973,1 vehicle in 2005[11,12]. However, there is scarce information addressing the impact of motor vehicles on air quality in Jordan. Studies carried out near highways have shown elevated concentrations of trace metals such as cadmium, lead, copper, zinc, nickel and chromium on vegetation and soil[13,14]. Al-Momani measured concentrations of gaseous pollutants inside tailpipes of some gasoline-fueled motor vehicles and found them to be in compliance with Jordanian standards[15].

None of the above studies has attempted to calculate emission rates from motor vehicles, which are crucial for future planning. Therefore, the objective of this study is to provide updated emission rates of gaseous pollutants from motor vehicles in Jordan.

Data Collection

Data were collected through three independent experiments. The first experiment was conducted by the staff at the Jordanian Ministry of Environment (JME) throughout Jordan during the year 2005 in order to insure compliance with the Jordanian standards. The second experiment was carried out at a smog-check station at the Department of Motor Vehicles and Drivers (DMVD) in Marka, Amman, where vehicles are supposed to pass smog test upon registration renewal. Because of the shortage in gas analyzers at the DMVD, only randomly selected vehicles are inspected. Vehicle owners tend to repair their vehicles prior to registration renewal in order to avoid penalties. In the third experiment, measurements were performed at a private smog-check station (Al-Azzam) in Irbid. Three types of gas analyzers were used in this study:

- SUN Gas Analyzer model SMP- 4000 (Sun Diagnostics, Norfolk, UK) available at Al-Azzam smog-check station in Irbid;
- Muller BEM Analyzer Type 8690 (Le Jardin d'Entreprises, CEDEX, France) available at the department of motor vehicles and drivers at Marka, Amman;
- AUTOCHEK 974/5 Analyzer (SPTC. LTD, Buchon Kyungki-Do, Korea) available at the Jordanian Ministry of Environment, Amman.

The three analyzers are calibrated every other week. Testing procedure is standard for all of them. Briefly, a special rode (sensor) connected to the analyzer is inserted into the tailpipe, the vehicle is idled, and the inspector pushes on the gasoline pedal in order to cover a wide range of the revolution per minute (rpm). The output of the Muller BEM Analyzer is the values of CO (carbon monoxide), CO_2 (carbon dioxide), HC (hydrocarbons), and λ (air to fuel ratio/ stoichiometric air to fuel ratio). The SUN, SMP- 4000 analyzer reads CO, CO_2, HC, and air to fuel ratio. AUTOCHEK analyzer is the only analyzer used in this study is capable of detecting nitrogen oxides (NO_x).

A special questionnaire was designed to be filled by vehicle owners while their vehicles are being smog-checked. The questionnaire contained inquiries about the vehicle, including vehicle make, year of manufacture, engine capacity, gasoline type (regular, super, or unleaded) and fuel consumption rate (kilometer traveled per liter of fuel).

Emission Rate Calculations

Combustion of hydrocarbons (HC) described by the chemical formula C_xH_y (gasoline for example) is represented by the following reaction [16]:

$C_xH_y + \lambda(x + 0.25y)O_2 \rightarrow zCO + (x-z)CO_2 + (0.5y)H_2O$ + hydrocarbons ....(1)

where

$\lambda = (A/F) / (A/F)_{stoichiometric}$ ....(2)

in which (A/F) is air to fuel ratio and $(A/F)_{stoichiometric}$ is the stoichiometric air to fuel ratio (16.5 for Jordanian gasoline)[17]; z is the number of moles of carbon monoxide (CO) formed per mole of gasoline,

$z = [CO] = 2(1-\lambda)(x + 0.25y)$ ....(3)

and,

$x - z = [CO_2]$= number of moles of carbon dioxide (CO_2) ....(4)

The last term in equation (1) represents any unreacted or partially burned hydrocarbons, which tend to form only small fraction in the vehicle exhaust (part per million), therefore we have ignored this term in order to develop a model to calculate emission rates for carbon oxides.

Jordan's oil refinery produces gasoline of the type C_8H_{17} with trace amounts of sulfur and lead compounds[17]. Replacing x and y with their values (8 and 17), equations 3 and 4 become:

$[CO] = 24.5(1-\lambda)$ ....(5)

and,

$[CO2]= 8 - 24.5(1-\lambda)$ ....(6)

Equations 5 and 6 are used to calculate number of moles of carbon oxides produced when burning one mole of gasoline. Emission rates are expressed as either mass of emitted pollutant per liter of consumed gasoline (ERL) or per kilometer traveled (ERKT). ERL is calculated using equations 5 and 6 after substituting molecular weights of gasoline, carbon monoxide and carbon dioxide. The mass of one liter of gasoline is simply the density (ρ, g/l) multiplied by the volume of 1.0 liter. The molecular weight of Gasoline (C_8H_{17}) is 113. Therefore, the number of moles of carbon monoxide and carbon dioxide emitted when burning one liter of gasoline are:

$[CO]_{liter} = 24.5(1- \lambda)\rho_{gasoline}/113$ ....(7)

and,

$[CO_2]_{liter} = (8 - 24.5(1- \lambda))\rho_{gasoline}/113$ ....(8)

where $\rho_{gasoline}$ is the density of the gasoline. Replacing the value obtained from the Jordanian Oil Refinery[17] of 730 g/l for the density of gasoline in equations 7 and 8 yields

$[CO]_{liter} = 158.27(1- \lambda)$ ....(9)

and,

$[CO_2]_{liter} = 51.68 – 158.27(1- \lambda)$ ....(10)

Emission rates of carbon oxides per one liter of gasoline consumed (ERL(CO) and ERL(CO_2)) in grams per liter are obtained by multiplying equations 9 and 10, respectively, by the molecular weights of carbon monoxide (28) and carbon dioxide (44), as follows.

ERL(CO) = 4431.6(1- λ)...(11)

and,

ERL(CO2)= 2237.9 – 6963.9 (1- λ) ....(12)

Emission rates of carbon oxides per kilometer traveled (ERKT(CO) and KTCO2)) in grams per kilometer are obtained by dividing equations 11 and 12 by distance traveled on one liter of gasoline:

ERKT(CO) = 4431.6(1- λ)/d ....(13)

and,

ERKT(CO2)= (2237.9 – 6963.9 (1- λ))/d..(14)

where d is distance traveled on one liter of gasoline.

Other emissions, such as nitrogen oxides and hydrocarbons, are not part of the combustion described in equation 1. Hydrocarbons are produced either through evaporation or burning of lubricants due to mechanical problems in the engine. Nitrogen oxides are formed when atmospheric nitrogen and oxygen react inside the combustion chamber under high temperatures.

A different approach is adopted to calculate emission rates for hydrocarbons and nitrogen oxides. Consider a section of the tailpipe with a cross-sectional area A and length L. The mass of a certain species (i) emitted from the tailpipe is Δm such that:

$\Delta m = C_i * V$ ....(15)

where:

C_i: concentration of pollutant i

V: volume of tailpipe section

$V=L*A$ ....(16)

But,

$L= v * t$ ....(17)

with v being the velocity of ejected gas from the tailpipe, and t the time (s) required to travel the length of the section (L).

Substituting equations 16 and 17 into equation 15 gives:

$\Delta m= Ci * v * t * A$ ....(18)

The emission rate in grams per second (ERi) is obtained by dividing equation 18 by time (t), giving

$ERi= C_i * v * A$..(19)

Emission rates of carbon dioxide, nitrogen oxides (NO_x), and hydrocarbons (HC) are calculated using the equations

$ER (CO_2) = C(CO_2) * v * A$ ....(20)

$ER (NO_x) = C(NO_x) * v * A$ ....(21)

$ER (HC) = C(HC) * v * A$ ....(22)

Dividing equations 21 and 22 by equation 20, the velocity and the cross-sectional area will be eliminated, therefore:

$ER(NOx) = (C(NOx)/ C(CO_2))* ER (CO_2)$.. (23)

$ER(HC) = (C(HC)/ C(CO_2)) * ER (CO_2)$ .... (24)

Equations 23 and 24 imply that emission rates for hydrocarbons and nitrogen oxides are calculated based on the emission rates of carbon dioxide (or carbon monoxide) by multiplying the latter with the fractional abundance of hydrocarbons or nitrogen oxides against carbon oxides in the tailpipe, as follows

$ERL(NO_x) = (C(NO_x)/ C(CO_2))* ERL(CO_2)$ ....(25)

$ERL(HC) = (C(HC)/ C(CO_2)) * ERL(CO_2)$ ....(26)

$ERKT(NO_x) = (C(NO_x)/ C(CO_2))* ERKT(CO_2)$ ....(27)

$ERKT(HC) = (C(HC)/ C(CO_2)) * ERKT(CO_2)$ ....(28)

Equation 11 through equation 14 are used to calculate emission rates for carbon oxides and equations 25 and 28 are used to calculate emission rates for nitrogen oxides and hydrocarbons, respectively.

Results and Discussion

Table 1 summarizes the data obtained from 520 tested vehicles. Data includes number of vehicles, their years of manufacture, tailpipe concentrations of CO, CO_2, HC, NO_x, and values of λ. About 60% of tested vehicles were manufactured before the year 1995. As could be learned from table 1, concentrations of tailpipe gases are within Jordanian standards of 5% maximum, 10% minimum, and 600 ppm maximum for CO, CO_2 and HC, respectively[12]. Our findings are in agreement with a previous study conducted by Al-Momani in Irbid directorate[15].

Table 1. Summery of raw data from tested vehicles.

Year of Manufacture	Number of cars	CO (%)	CO_2 (%)	HC (ppm)	NO_x (ppm)	λ
≥ 2004	30	0.00 – 10.30	9.30 – 16.60	85 – 841	0 – 791	0.79 – 1.00
2003 - 2001	53	0.00 – 9.84	6.68 – 16.50	122 – 2080	0 – 598	0.73 – 2.00
2000 - 1998	75	0.04 – 10.68	5.78 – 18.41	41 – 939	0 – 980	0.34 – 1.31
1997 - 1995	83	0.03 –11.05	5.37 – 16.20	32 – 3206	0 – 357	0.69 - 2.21
1994 - 1992	70	0.09 – 27.00	0.60 – 15.70	58 – 2550	0 – 419	0.67 – 3.00
1991 - 1989	34	0.19 – 12.26	1.24 – 15.00	80 – 922	0 – 161	0.62 – 2.80
1988 - 1986	30	0.09 – 9.24	6.54 – 14.70	60 – 2963	0 – 221	0.50 - 2.20
1985 -1983	44	0.11 – 16.70	1.68 – 13.67	60 – 2388	0 – 224	0.71 – 3.00
1982 - 1980	41	0.06 – 12.42	4.64 –15.70	138 – 2095	0 – 177	0.25 – 2.36
1979- 1977	39	0.08 – 12.23	6.28 – 14.70	118 – 1700	0 – 176	0.67 – 1.80
1976 - 1974	14	0.30 – 11.26	1.93 – 15.00	206 – 1414	0 – 57	0.70 – 2.40
≤ 1973	10	1.14 – 10.53	5.33 – 13.00	226 – 1142	0 – 91	0.79 – 1.01

Measurements Precision

The uncertainty of the three analyzers was estimated by repeating the test for a one car several times (results are shown in tables 2-4). Based on the observations of this part, the uncertainty of the findings of this study is 10%.

Table 2. Precision of the SUN Gas Analyzer model SMP- 4000 at Al-Azzam smog-check station in Irbid.

Trial	CO (%)	CO_2 (%)	HC (ppm)	λ
1	4.21	15.61	122	0.88
2	5.15	18.51	146	0.95
3	4.89	17.18	112	0.82
4	3.99	16.23	125	0.79
5	4.67	15.24	117	0.83
6	5.03	15.00	132	0.91
7	5.15	14.70	145	0.90
8	4.28	13.67	148	0.88
9	4.16	15.70	129	0.81
10	4.01	17.08	108	0.86
Average	4.55	15.89	128	0.86
STDEV	0.47	1.40	14	0.05
Uncertainty %	10.42	8.83	11	5.83

Table 3. Precision of the Muller BEM Analyzer Type 8690 available at the department of motor vehicles and drivers at Marka, Amman.

Trial	CO (%)	CO_2 (%)	HC (ppm)	λ
1	4.65	18.92	442	0.91
2	4.12	18.54	380	0.79
3	4.82	17.63	485	0.89
4	4.50	16.50	412	0.93
5	4.74	18.33	389	0.90
6	4.90	16.47	420	0.86
7	4.62	18.02	465	0.80
8	4.25	18.22	399	0.85
9	4.41	16.22	480	0.77
10	4.01	17.24	452	0.92
Average	4.50	17.61	432	0.86
STDEV	0.30	0.96	38	0.06
Uncertinity %	6.7	5.4	8.8	6.7

Table 4. Precision of the AUTOCHEK 974/5 Analyzer available at the Jordanian Ministry of Environment, Amman.

Trial	CO (%)	CO_2 (%)	HC (ppm)	NO_x (ppm)	λ
1	3.54	12.99	350	290	0.89
2	3.02	14.67	393	310	0.93
3	3.07	15.32	417	270	0.95
4	3.42	16.50	375	312	0.86
5	3.85	13.62	462	335	0.90
6	3.67	13.99	423	285	0.86
7	3.12	14.88	349	268	0.79
8	3.25	15.26	419	300	0.87
9	3.64	14.93	426	302	0.82
10	3.55	13.84	371	278	0.84
Average	3.41	14.60	399	295	0.87
STDEV	0.28	1.01	37	21	0.05
Uncertinity %	8.3	6.9	9.3	7.1	5.6

Emission Rates

Average emission rates for gaseous pollutants per one-liter gasoline consumed and per kilometer traveled are given in table 5. Numbers in the second row of table 5 are calculated based on the estimation that, on average, a car travels 9.54 km on one liter of gasoline.

Table 5: Average emissions rates of gaseous pollutants from vehicle tailpipes per liter of consumed gasoline (g/l) and per kilometer traveled (g/km).

Emission Rate	CO (g)	CO_2 (g)	HC (g)	NO_x (g)
Per Liter of Consumed Gasoline	239.0	1910.1	6.1	1.1
Per Kilometer Traveled	33.9	198.4	1.0	0.1

In addition to calculating average emission rates of vehicles, factors that affect emission rate including year of manufacture, engine size in cubic centimeter (cc), and fuel type (regular, super, or unleaded gasoline) are also examined. Results are illustrated in figures 1 through 4. Figure 1 shows that newer vehicles are cleaner than older vehicles (vehicles manufactured before 1994), as they emit less CO_2, CO, and HC per kilometer traveled. However, it can be seen that newer vehicles emit more NO_x than older vehicles, in agreement with a previous study by Gertler et al.,.[18] In an attempt to explain why newer vehicles emit more NO_x, Gertler et al., have argued that although newer vehicles emit more NO_x, the ratio NO_x/CO_2 is lower.[18] Our findings do not support that argument, since we found that NO_x/CO_2 ratio is also higher for newer vehicles (figure 2).

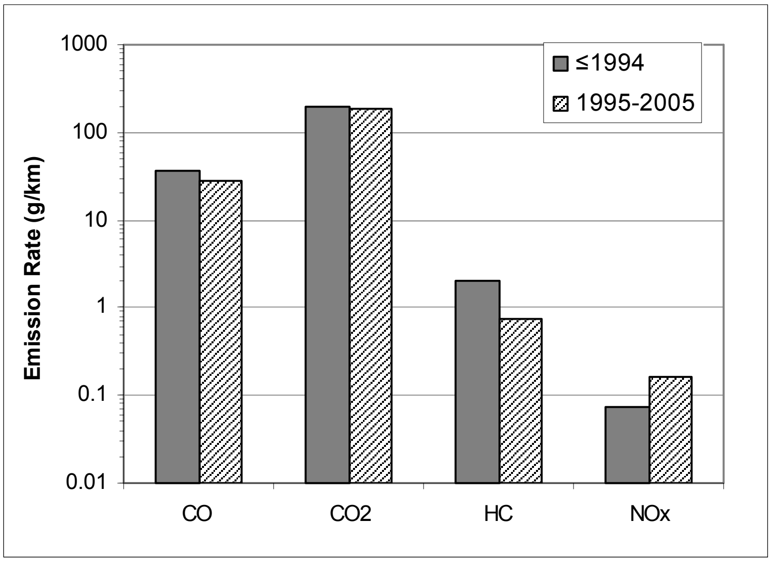

Figure 1. Emission rates of CO, CO_2, HC, and NO_x (g/km) from motor vehicles and their dependence on year of manufacture.

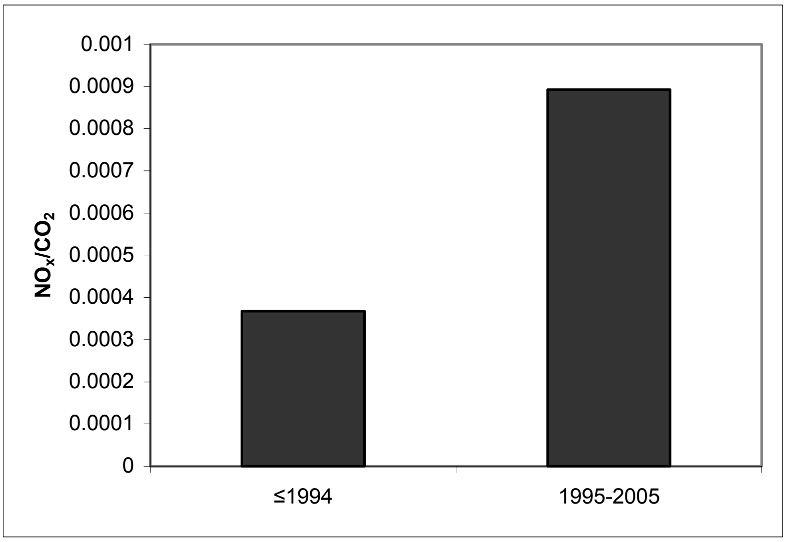

Figure 2. NO_x to CO_2 ratio versus year of manufacture

Figures 3 and 4 illustrate the dependence of gaseous emission rates on gasoline type. It is readily seen from figure 3 that vehicles fueled by super gasoline emit more CO_2, less CO and les HC than those fueled by regular gasoline, which indicate that super gasoline has better combustion efficiency. Figure 4 shows the dependence of emission rates on engine size. It is evident that vehicles with high engine capacity (>1500 cc) are potential emitters; they emit more carbon oxides and hydrocarbons because they burn more gasoline than vehicles with smaller engine when traveling similar distances.

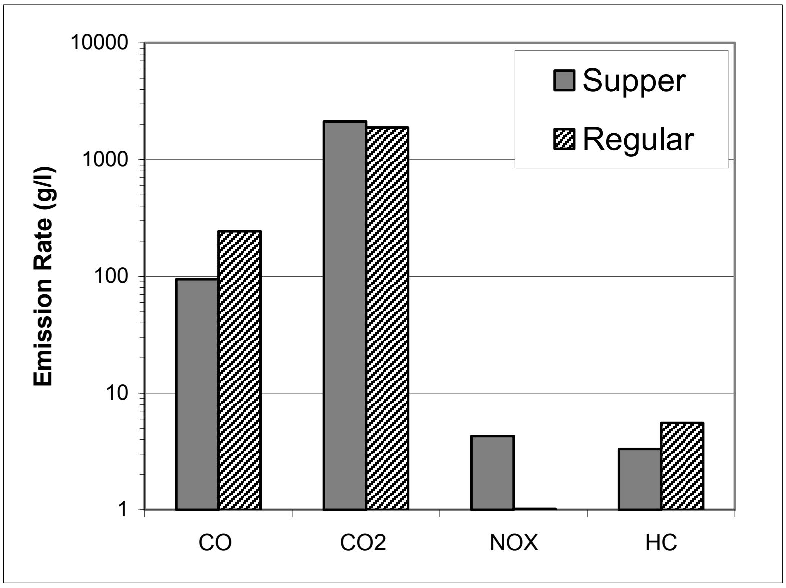

Figure 3. Emission rates of CO, CO_2, HC, and NO_x (g/l) from motor vehicles and their dependence on gasoline type.

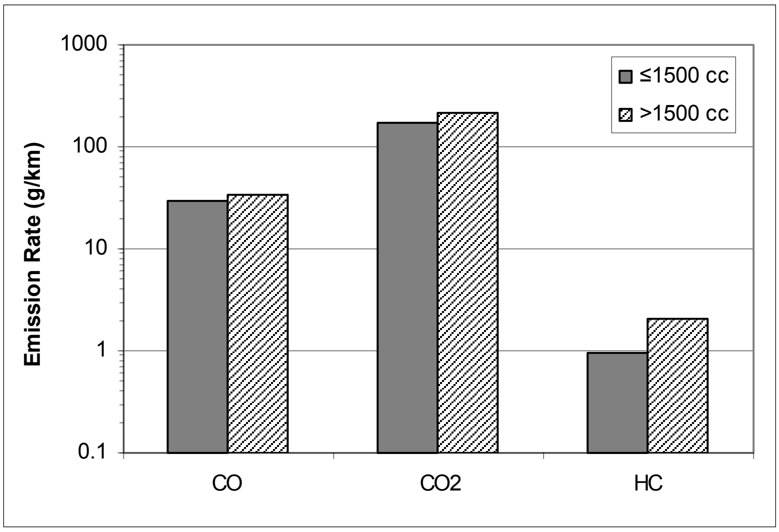

Figure 4. Emission rates of CO, CO_2, and HC(g/km) from motor and their dependence on engine capacity.

Comparison with Previous Studies

Table 6 shows a comparison of our findings with previous studies[18-22]. Although, the experimental conditions are different among presented studies, our findings compare favorably with their findings. In the first two studies (Gertler et al. and Pierson et al.), data were collected in Tuscarora Mountain Tunnel where vehicles are operated in steady state mode. Therefore, their findings are expected to be lower than the findings of the current study. In addition, emission rates reported in this study are expected to be high because pollutants are collected directly from the tailpipe before dilution in the open atmosphere.

Table 6. Emission rates observed in previous studies (g/km).[18-22]

Study	Measurements	CO	CO_2	HC	NO_x
Gertler et al.	Tunnel	1.93	154.38	0.4	0.22
Pierson et al.	Tunnel	3.03	143.84	0.18	0.24
Ristovskia et al.	Dynamometer	0.0 - 0.7	249 - 692	-	3 - 10
Corsmeiera et al.	On-Road	2.62	-	-	1.08
Environmental Protection Agency	Modeling	7.7	227	1.0	0.6
This Study		33.87	198.4	1.04	0.11

Summary and Conclusions

Motor vehicles are potential sources of air pollution in Jordan. Information about ambient levels and the contribution of motor vehicles to them is scarce. This study was carried out in order to obtain emission rates from gasoline-fueled motor vehicles. Several tasks were performed, including gathering data from previous field experiments carried out by the Jordanian Ministry of Environment, measuring tailpipe concentrations of gaseous air pollutants from randomly selected motor vehicles at two stations; DDVL station at Marka, Amman, and Al-Azzam smog-check station in Irbid, and then analysis of collected data based on combustion theory. Specific conclusions of this study are:

- Concentrations of tailpipe gaseous pollutants are within Jordanian standards;
- Average emission rates from individual vehicles are 33.9, 198.4, 1.0, and 0.1 g/km for CO, CO_2, HC, and NO_x, respectively;
- Emission rates from motor vehicles depend on several factors, including year of manufacture, engine size, and type of gasoline used; and
- Motor vehicles that use regular gasoline, old motor vehicles, and motor vehicles with larger engines tend to emit more gaseous air pollutants.

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