Models to estimate emissions from railway transport systems

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Pollution is a growing problem in both developed and developing countries. While most attention has been concentrated on emissions from road traffic, recently, the attention is to be converted to the off-road transportation system. One of the most common off-road traffic modes is the rail transport system. The purpose of this paper is to derive new models to estimate pollution from railway traffic, in order to evaluate railway systems. Factors affecting energy consumption in railway system were analyzed. Data analysis of energy consumption on rail networks has been performed. Energy consumption models as a function of geometrical characteristics of track, and operational characteristics of trains has been estimated. Calibrated specific emission parameters, as a function of type of energy consumed, have been determined. Calibrated rail traffic emission models have been derived. Finally, applications of the models have been performed on a regional rail system in Alexandria city, namely Abou Kir Railway Line.

التلوث هو مشكلة متنامية فى كل من الدول الصناعية والدول النامية. ولقد كان التركيز أساسا على التلوث الناتج من أنظمة النقل على الطرق, وحديثا بدأ الاهتمام بالتلوث الناتج عن أنظمة النقل الأخرى ومنها أنظمة النقل على السكك الحديدية. إن الهدف الرئيسي من هذا البحث هو بناء نماذج رياضية جديدة لتقييم الملوثات الناتجة عن الحركة على السكك الحديدية وللوصول الى هذا الهدف تم دراسة العوامل التى تؤثر في استهلاك الطاقة على الخطوط الحديدية، و تحليل بيانات خاصة عن استهلاك الطاقة بالسكك الحديدية بغرض بناء نماذج لها. ولقد تم أيضا بهذا البحث بناء نماذج رياضية لاستهلاك الطاقة لقطارات السكك الحديدية كدالة فى العناصر الهندسية للسكة، والعناصر التشغيلية للقطارات. وقد تم تحديد العناصر النوعية للتلوث كدالة فى نوعية الوقود المستخدم.و أخيرا تم بناء نماذج تقييم الملوثات الناتجة من أنظمة النقل بالسكك الحديدية وعمل تطبيقات عملية لها لتقييم الملوثات الناتجة من خط ابي قير الحديدي بمدينة الإسكندرية .

Keywords: Railway emission, Energy consumption, Models, Diesel /Electric trains

1. Introduction

Railways are usually seen as an environmentally friendly option for transport. This has recently led to considerable interest in the expansion of their role in the movement of freight, in long distance high -speed passenger travel, and also to solve congestion in densely populated areas, in the form of light rail and regional rail systems. Railways are therefore entering a new era of higher speeds and higher capacities both for inter-city and urban systems and are set to play their part in reducing the environmental burden caused by steady growth in road transport. The purposes of this paper are to develop new models to estimate emissions from railway -transport systems, as well as to evaluate railway systems. This paper is divided into four major sections. In the first section factors affecting fuel consumption in railway system were analyzed. In the second sections energy consumption models for diesel and electrically operated trains have been derived. The third section identifies calibrated specific emission parameters of railway traffic, as well as introduces new models to estimate pollution from railway traffic. Finally, applications of the models to evaluate railway systems in Alexandria city have been performed in the last section.

2. Factors affecting energy consumption in railway systems

The main factors affecting energy consumption in a railway system may be classified into:

- Operational factors,
- Locomotive characteristics,
- Quality and type of fuels used,
- Network characteristics,
- Utilization factors,
- Type of railway service, and

• Organizational factors.

The operational factors may include the average train weight and speed. In this paper, data from [1] were analyzed to study the effect of train weight on the specific energy consumption (kJ/ton.km) of a diesel operated rail system. The analysis shows that an increase in the average weight of trains would result in decline in specific energy consumption (fig. 1). Though with the increase in average weight of trains, total fuel consumption increases, but per unit of transport output (ton.km), requirements of fuel would be less, because of the higher utilization of the hauling capacity of the locomotive.

Speed of trains is an important factor in determining energy consumption of railway transport modes. As shown in fig. 2 moderate and high speeds are crucial determinant of the magnitude of forces of inherent resistance to the train's motion. Reductions in speed thus decrease the magnitude of these forces and the effective energy requirements for vehicle propulsion. Thus, reduction in moderate and high speed indicates reduction in specific energy consumption. However, excessively low speeds do not necessarily result in lower energy consumption, because engines have lower energy efficiencies when performing under the partial loads included by lower speeds. Type of engine used, condition of locomotive, tractive effort of engine and age of engine, affect the specific energy consumption of railway systems. These factors are interrelated. The age of engine affects the general condition of the locomotive.

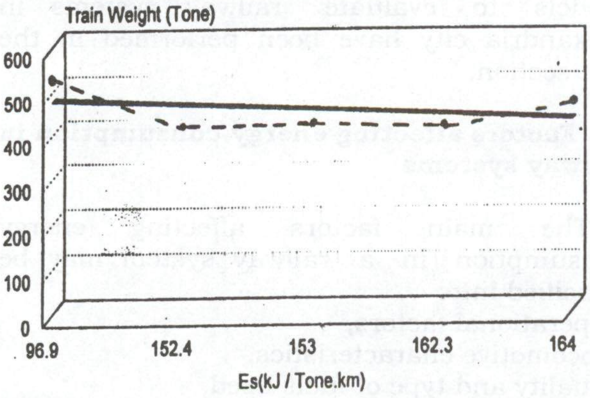

Fig. 1. Effect of train weight on specific energy consumption of diesel operated inter-city rail system.

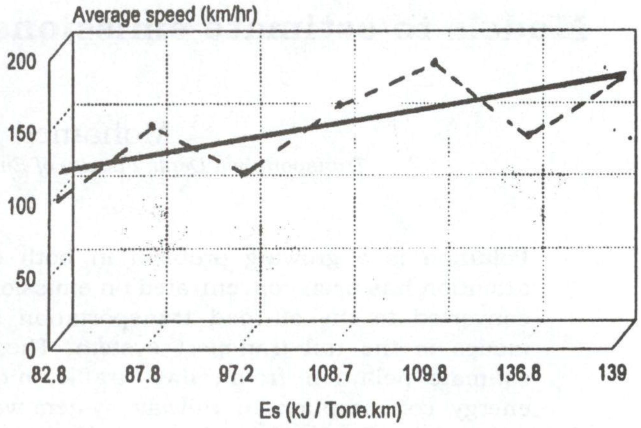

Fig. 2. Effect of average train speed on specific energy consumption of diesel operated inter-city rail system.

If the proportion of older engines increases in the locomotive fleet, it affects the specific energy consumption of the system. In this paper, data from [2] were analyzed to study the effect of engine age on the specific energy consumption. The results are shown in figs. 3-5. Fig. 3 shows these effects in case of electrical suburban rail system. An increase of 100% of the specific energy consumption (kWh/passenger.km), for an electrical suburban rail system, has been recorded for engine with 25 year old. Fig. 4 illustrates the effects of engine age on specific energy consumption of electrical inter-city trains. The increase of specific energy consumption due to 10 years oldness is 11%. In case of inter-city diesel operated trains the increase of specific energy consumption has been recorded to be 14% for an engine with 15 years old (fig. 5).

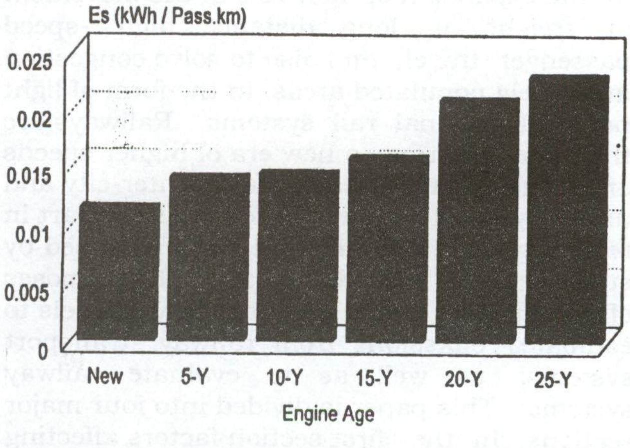

Fig. 3. Effects of engine age on specific consumption of electrical suburban rail system.

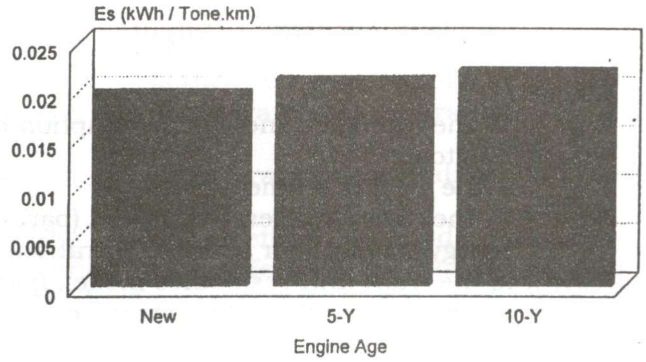

Fig. 4. Effects of engine age on specific consumption of electrical inter-city rail system.

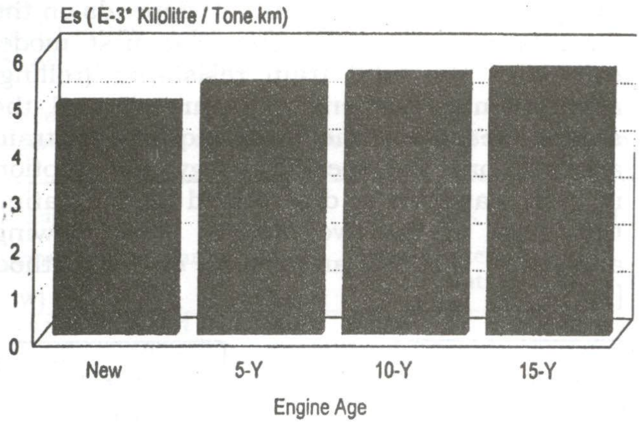

Fig. 5. Effects of engine age on specific consumption of diesel operated inter-city rail system.

Tractive effort of an engine varies with the type of gradient and speed of the train. The engine with greater tractive effort will consume considerably more fuel than the one with lesser tractive effort, but the specific energy consumption in this case will be less.

The quality and type of fuel affect also the specific energy consumption of railway systems. The quality of coal, for example, used in power plant of electrical railway system affects the kWh/ton.km used in the system. The specific energy consumption is also related to the type of fuel used.

The specific energy/fuel consumption is affected also by the geometrical characteristics of track network (gradient, horizontal curves, number of intermediate stations, and distances between stations). On a flat rail section, the fuel consumption would be less than on an up- gradient, because the greater pulling effort is required by engine in the later case. The effects of number of intermediate stations on specific energy consumption can be seen in fig. 6. This Figure illustrates that increasing in the number of station leads to increasing in the specific energy consumption. As shown in fig. 7 the distance between the stations affects the specific energy consumption adversely.

Locomotive and wagon utilization factors may also affect specific energy consumption in a railway system. Engine kilometers per day per engine, net ton kilometer per locomotive per day, and ton kilometer per train engine hour, are various indicators of capacity utilization. If the value of these indicators increases, it would imply that the performance of engine has improved and it would be expected that the fuel consumption rate would decline. Improvements of locomotive and wagon utilization are interrelated, because they represent increase in transport output. If production of transport output increases with the improvement in the performance of engines, the specific energy consumption would fall.

Fuel consumption is also dependent on the type of services for which trains are used. For the passenger services, the specific energy consumption is usually found to be more than that on freight services. The main reason for this is that the passenger trains are lighter than the freight trains. Thus the ethis factor can be examined with the help of the average weight of the train.

Finally, the organizational factors like planning, organization of system, staffing, and controlling, also, affect the total fuel consumption of a railway system.

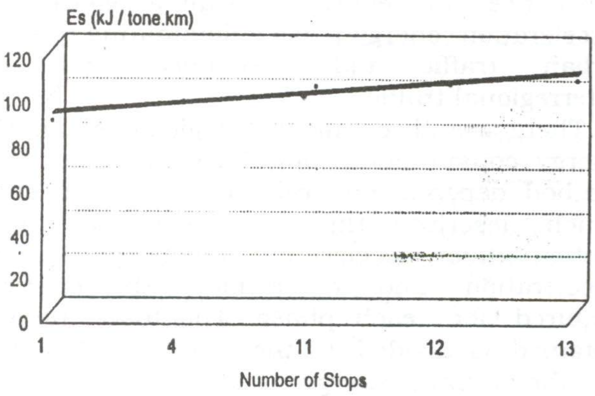

Fig. 6. Effects of number of intermediate stations on specific energy consumption of diesel operated inter-city rail system.

on the specific energy consumption can be derived from table 3. An increase of 2% of the specific energy consumption per station has been determined.

The proposed models to estimate specific energy consumption for railway system is derived using the third method. The models for diesel operated trains depend mainly on data collected from the German ICE trains, and the French TGV trains. Data from [3,4] were analyzed and then, regression models were formulated. The result of the regression analysis for diesel operated trains is the following multiple regression models:

$$Esd = a_o + b_1 V_{av.} + b_2 N_s + b_3 g_{av.}, \quad (1)$$

$$Esd` = b_o + C_1 W + C_2 V_{av.} + C_3 d + C_4 N_s + C_5 g_{av} . \quad (2)$$

Where;

Esd is the specific energy consumption in kWh/ ton-km, for diesel operated trains,

Esd is the specific energy consumption in kJ/ton*km for diesel operated trains,

E is the specific energy consumption in kWh/km,

$V_{av.}$ is the average train speed in km/hr.,

N_s is the number of intermediate stations,

d is the distance between end-stations in km,

g_{av} is the average track gradient in distance d (o%),

W is the Weight of train in tons, and

a_o, b_1, b_2, b_3, b_o, C_1, C_2, C_3, C_4, and C_5 are model parameter, table 4.

These models describe the transport mode characteristics through the average speed, and the train weight variables, as well as the track characteristics through the distances between end-stations, number of intermediate stations, and average gradient of track.

Table 4
Model parameters, diesel operated trains

Esd – parameters		Esd` - parameters	
Parameter	Value	Parameter	Value
Ao	0.0197	Bo	71.3777
B1	0.0001	C1	0.0379
B2	0.0006	C2	0.4769
B3	0.0002	C3	0.0316
R (regression coefficient)	0.9031	C4	2.0773
		C5	0.8198
		R	0.9032

4. Models to estimate energy consumption for electric trains.

Similarly, data of electrical trains were collected, and analyzed to estimate energy consumption models of electrical trains. Table 5 shows samples of these data. This table also shows the effects of train weight and other train operational and track geometrical factors on the specific energy consumption. An increase in train weight of 18% implies a decrease in specific energy consumption of 13%. The results of the regression analysis for electrical trains are the following multiple regression models:

$$Ese = a_o + b_1 V_{av} + b_2 d + b_3 W , \quad (3)$$

$$Ese` = b_o + C_1 V_{av.} + C_2 d + C_3 W , \quad (4)$$

where;

Ese Specific energy consumption in kWh/ ton-km, for electrical trains,

Ese` Specific energy consumption in kJ/ton-km, for electrical trains, and

a_o, b_1, b_2, b_3, b_o, C_1, C_2, and C_3 are model parameter, table 6.

Table 5
Energy consumption data of electrical trains [5, and own calculations].

V_{av} (km/hr.)	D (km)	Intermediate stations	Weight (Ton)	E (kWh/km)	E_s (kWh/ ton *km)	E_s` (kJ/ ton *km)
145	456	2	333	9.94	0.0298	107.28
103	456	10	453	15.63	0.0345	124.20
105	540	10	462	13.98	0.0301	108.36
90	53	3	105	5.47	0.0521	187.56

Table 6
Model parameters, electric operated trains.

Ese – parameters		Ese` - parameters	
Parameter	Value	Parameter	Value
Ao	-0.09234	Bo	121.0155
B1	0.00053	C1	-0.02144
B2	-0.00025	C2	-0.02038
B3	0.00031	C3	0.0633
R (regression coefficient)	0.875	R	0.9997

5. Emission parameters as a function of type of energy consumed

The second stage of estimating the models to evaluate pollution from railway traffic is the determination of the emission parameters. The main emissions produced from railway traffic are:

- Carbon Monoxide CO,
- Hydraulic Carbon HC,
- Nitrous Oxides Nox,
- Sulfur Dioxide SO_2,
- Carbon Dioxide CO_2, and
- Particulate.

Emission factors generated from railway traffic can be identified in different forms, as power specific emission factors (g emissions/kWh), or as fuel specific emission factors (g emissions/kg fuel), or as traffic-volume specific emission factors (g emission / passenger.km or g/ton.km).

Table 7 illustrates typical power specific and fuel specific emissions factors for diesel trains.

Table 8 shows traffic-volume specific emission factors for diesel trains.

The emission factors for electric trains depend on the methods and fuel used to produce electricity. In this case the emissions are not produced locally but at remote sites. Tables 9 and 10 illustrate typical emission factors for electric inter-city trains and regional rail transit, respectively.

From these tables, it can be seen that using natural gas to produce electricity for train operations produces minimum pollution than using coal or heating oil. A reduction of 45 % of CO_2, 50% of CO, 100 % of SO_2 per kWh can be achieved when using natural gas.

Table 7
Typical power specific and fuel specific emissions factors for diesel trains [6]

Emission	Power specific (g/kWh)		Fuel specific (g/kg)	
	Range	Average	Range	Average
CO	1 – 10	3.9	5 – 40	22
HC	0.5 – 4.0	2.0	3 – 25	11
Nox	6 – 16	10.7	30 – 70	53
Particulate	0.2 - 1.2	0.6	1 – 6	3
SO_2	0.2 – 2	0.8	1 – 10	4
CO_2	604-700	640	3180	3180

Table 8
Traffic-volume specific emission factors for diesel trains, (g/passenger.km) [7]

Train Type	Energy consumption MJ/pass.km	CO_2	SO_2	Nox	HC	CO	Particulate
Inter-city	0.52	36	0.01	0.6	0.03	0.1	0.02
Inter-regional	0,89	66	0.02	1.2	0.05	0.2	0.06
Regional	0.90	66	0.02	1.6	0.2	0.4	0.1

Table 9
Typical Emission factors for electric trains, (power plant produces 16.66 Hz electricity) [8]

Primary energy	CO_2 g/kWh	CO g/kWh	HC G/kWh	Nox g/kWh	SO_2 g/kWh
Water energy	0.0	0.000	0.000	0.000	0.000
Coal	991	0.201	0.031	1.178	1.759
Heating oil	752	0.096	0.067	1.553	3.969
Natural gas	547	0.010	0.049	1.386	0.000

Table 10
Emission factors for electrical powered regional rail transit [9]

	CO_2 g/kWh	CO g/kWh	HC g/kWh	Nox g/kWh	SO_2 g/kWh	Particulate g/kWh
Regional rail transit	793	0.103	0.0309	2.16	2.57	0.082

In general form, using electrical operated trains produces minimum pollutants than using diesel operated trains. However, the specific emission factor for CO_2 and SO_2 is greater in case of electrical trains.

6. Emission models

Having determined the specific energy consumption models of rail systems (diesel and electrical operated), and the specific emission parameters, the proposed emission model can be formulated as:

$$P_I = E_s * T_v * E_{f,I} \quad . \qquad (5)$$

Where;
P_I is the emission (I) produced from railway transport system in gram emission /year,
E_s is the specific energy consumption of rail system in kWh/ton-km,
Tv is the transport volume in ton-km/year, and
$E_{f,I}$ is the specific emission factor of pollution (I) in g/kWh, (table 7, 9, and 10).

7. Applications

The regional rail system in Alexandria city, namely Abou Kir Railway Line, has been chosen for a case study to evaluate the emissions produced from this type of rail transit system. The Abou Kir railway line is a double track diesel operated regional rail system. It connects the central areas in Alexandria city with the suburban area Abou Kir. The regional rail system has a length of 22.11 km, and an average gradient (g_{av}) of 0.9%º. It contains 14 intermediate stations. The train weight is estimated to be 350 tons, and its average speed to be 60 km/hr. There are 194 trains scheduled per day, from which 97 trains serve in each direction. The trains have a capacity of 1500 passenger per train, more than 145,500 passenger can be carried in each direction per day.

Applying the models number (1) and (2), the specific energy consumption can be estimated to be 0.03428 kWh/ton.km, and 123.4 kJ/ton.km. Applying the model number (5), and parameters in table 7, the daily emissions produced from the regional rail system in Alexandria city can be estimated to be 9 kg CO, 4.7 kg HC, 24.9 kg Nox, 1.4 kg particulate, 1.9 kg SO_2, and 1489 kg CO_2. For comparison, In case of electrification of the Abou Kir railway line, the specific energy consumption can be estimated to be 0.04243 kWh/ton.km. The daily emissions produced may be estimated to be 0.296 kg CO, 0.89 kg HC, 6.22 kg Nox, 0.236 kg particulate, 7.4 kg SO_2, and 2284 kg CO_2.

In case of using natural gas as primary energy for electrification, the daily emissions produced from the regional rail system in Alexandria can be estimated to be 0.0288 kg CO, 0.1411 kg HC, 3.99 kg Nox, and 1575 kg CO_2.

An equivalent road bus system, petrol operation, which transports the same passenger volume, may produce daily 27.9 tons CO_2 and CO_2 equivalent emissions (Nox, and CH_4).

8. Conclusions

This paper has focussed on the quantification of emissions produced from railway traffic. Emission production and energy consumption are interrelated sectors. Reduction in energy consumption leads to reduction in pollution production. New analytical energy consumption models for diesel and electrical operated trains as well as new models to estimate pollution from railway systems were derived. These models show the dependence of energy consumption and emission production on important factors such as train operational factors, network characteristics, quality and types of fuel used, and type of railway service. It is believed that the models described in this paper are both generalized and practical. They can also lead to a better understanding of railway pollution sector.

Data analysis of energy consumption of railway systems indicates that an increase in the average weight of trains would result in decline in specific energy consumption and consequently emission production. 18% increase in train weight leads to 13% decreasing in the specific energy consumption. Reduction in moderate and high speeds of trains indicates reduction in specific energy consumption. An increase of 43% of the specific energy consumption has been recorded for an average gradient of 0.76 ‰, over a distance of 89 km, and a speed increase of 65 km/hr. Increasing in the number of station leads to increasing in the specific energy consumption. The effect of number of stations on the specific energy consumption, due to acceleration and deceleration, represents 2% increase of the specific energy consumption per station. The distance between the stations affects the specific energy consumption adversely. Locomotive age has also an adversely effect on energy consumption and emission production. An increase of 100% of energy consumption may be occurred for an electrical suburban rail system due to 25 years engine oldness. Using natural gas to produce electricity for train operations produces minimum pollution than using coal or heating oil. A reduction of 45 % of CO_2, 50% of CO, 100% of SO_2 per kWh can be achieved when using the natural gas. In general form, using electrical operated trains produces minimum pollutants than using diesel operated trains. However, the specific emission factor for CO_2 and SO_2 is greater in case of electrical trains.

Applications of the derived models on the regional rail system in Alexandria City, Abou Kir rail line, indicate the following facts:

- The specific energy consumption can be estimated to be 0.03428 kWh/ton.km, or 123.4 kJ/ton.km in case of diesel operated trains (current system), and 0.04243 kWh/ton.km, in case of electrification the rail line,
- The daily emissions produced from the regional rail system in Alexandria city can be estimated to be 9 kg CO, 4.7 kg HC, 24.9 kg Nox, 1.4 kg particulate, 1.9 kg SO_2, and 1489 kg CO_2,
- A reduction of 29 fold of CO, 4 fold of HC, 3 fold of Nox, and 5 fold of particulate, and increasing of 54% of CO_2, and 290% of SO_2, can be achieved in case of electrification the regional system,
- A reduction of 311 fold of CO, 32 fold of HC, 5 fold of Nox, and increasing of 6% of CO_2 can be achieved in case of using natural gas as primary energy in electrification of the regional system ,
- An equivalent road bus system, petrol operation, which transports the same passenger volume, may produce 27.9 tons CO_2 and CO_2 equivalent emissions (Nox, and CH_4).

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Received July 30, 2001
Accepted November 6, 2001