The Effect of Design Parameters of Sharp Curved Tracks on
Wear and Lifetime of Rails for Cairo Underground Metro Lines

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Abstract: Subways are considered the backbone and the most important urban transportation mean in Greater Cairo in comparison with the other inner-city networks, as they contribute in solving traffic congestion, not only in the heart of the megalopolisy but also in many places in the greater city. Tracks of these subways contain many short radii curves especially in Line No. 2 of Greater Cairo metro network, where excessive lateral rail wear has been observed and measured on the outer rails of these curves. Analysis and evaluation of the measured lateral rail wear values, the mathematical equations which connect these values with the designed parameters, e. g. running speed, accumulated wheel loads, curve radius…etc.; that had been carried out in year 2002 are presented in this paper. Validation for that obtained models using wear records that have been measured in May 2012 is done and will be outlined too. Also, effect of design parameters of the sharp curved tracks on recent cost of worn rails is included. Conclusions and recommendations that contribute in reduction of lateral wear phenomenon and lead to optimal rail lifetime have been introduced in the end of the paper.

Key words: metro lines, rail wear, lubrication of curved rails, rail maintenance cost

Introduction

Nowadays, the ministry of transport in Egypt intends to complete construction of Greater Cairo Metro Network due to the greater demand of passengers. More than 3 million of Greater Cairo residents use the network daily in their transportation [1]. As railroads of these subways are usually constructed along narrow streets, either in tunnels or on ground surface, the track designer is often compelled to choose short radii curves in the layouts.

Wheel /rail contact results in many serious phenomena such as air-born noise, vibrations, rail wear and rail corrugations, etc. [2]. Rail wear is the most important reason for replacing rails in subways, especially in Line No. 2 of Greater Cairo metro network as shown in Figure 1. This figure gives a photo for worn rails that were replaced from Line No. 2 and stored in Shoubra workshop.

In year 2002, a study for lateral and vertical rail wear had been carried out by the author to obtain two mathematical models for the measured curve wear values and track parameters. Outline for the analysis that was included in that study is presented hereafter in item 2 (page 4) of this paper [3].

When the measurements of lateral wear reached the maximum allowable values, the worn rails were replaced by new ones during the period from 2000 to 2002; where the values of lateral wear have been recorded up till now. The recent records that have been measured in May 2012 will be used hereafter in item 3 to validate the mathematical model of lubricated rails that have been previously obtained in 2002.

Also; a general equation for calculation of curved rail lifetime in years have been derived and is given in item 4.

The effect of design parameters on the maintenance recent cost of dry and lubricated outer rails of these curves has been analyzed in item 5. Results of the validation process are also presented. Recommendations to get suitable solutions for reducing rail wear phenomenon and to obtain optimal rail lifetime will be introduced in item 6 of the paper.

Figure 1: Worn rails replaced from Line No. 2 and stored in Shoubra workshop.

1. Greater Cairo Metro Network

The studies agreed that the main solution to meet the requirements of urban transport inside Greater Cairo region necessitates execution of a network of underground metro lines to connect the different districts within the enlarged city center. Up till now; this network includes three different lines as shown in Figure 2.

1.1 Line No. 2 Permanent Way

The term permanent way means tracks, switches, crossings and track support systems. Track support used on ground surface is different from that used in the tunneling section, however tracks include many short- radii curves (200 to 300 ms) in the different sections as shown in Figure 2. Characteristics of these curves and recent values of lateral rail wear are indicated in Table 1[4,5].

Table 1: Characteristics of some Curves in Line 2

Curve N0.	Location (km)	Length (m)	Curve Radius R (m)	Design Speed v1 (km/h)	Super-elevation (mm)	Records of lateral wear (May 2012) mm
1	8.300-8.406	106	200	60	115	8
2	13.879-14.193	314	210	65	110	7
3	7.144-7.162	18	223	52	50	4
4	6.890-7.010	120	250	70	135	4
5	0.969-1.163	194	253	63	90	4
6	8.768-8.873	105	253	65	100	4
7	6.897-6.998	101	253	70	135	4
8	7.818-7.847	29	300	71	100	7
9	2.598-2.640	42	353	61	25	8
10	2.760-2.800	44	753	80	30	2

1.1.1 Permanent Way on Ground Surface

Permanent way on ground surface tracks consists of embankment, ballast bed, rails, sleepers and fasteners. The ballast bed consists of loose, coarse grain ballast. Thickness of ballast is 25 to 30 cms measured from the underside of sleepers. Rails used are UIC54 section, welded by thermit every 18 m length. All rails are manufactured with 900A grade steel [3]. Glued insulated joints are used to separate track circuits for operating the automatic block system. Twin block concrete sleepers are used for the two main tracks. Distance between sleepers is 60 cms. Weight of the sleeper is 250 kgs. Vossloh Type system is used for fastening all tracks to achieve more track elasticity.

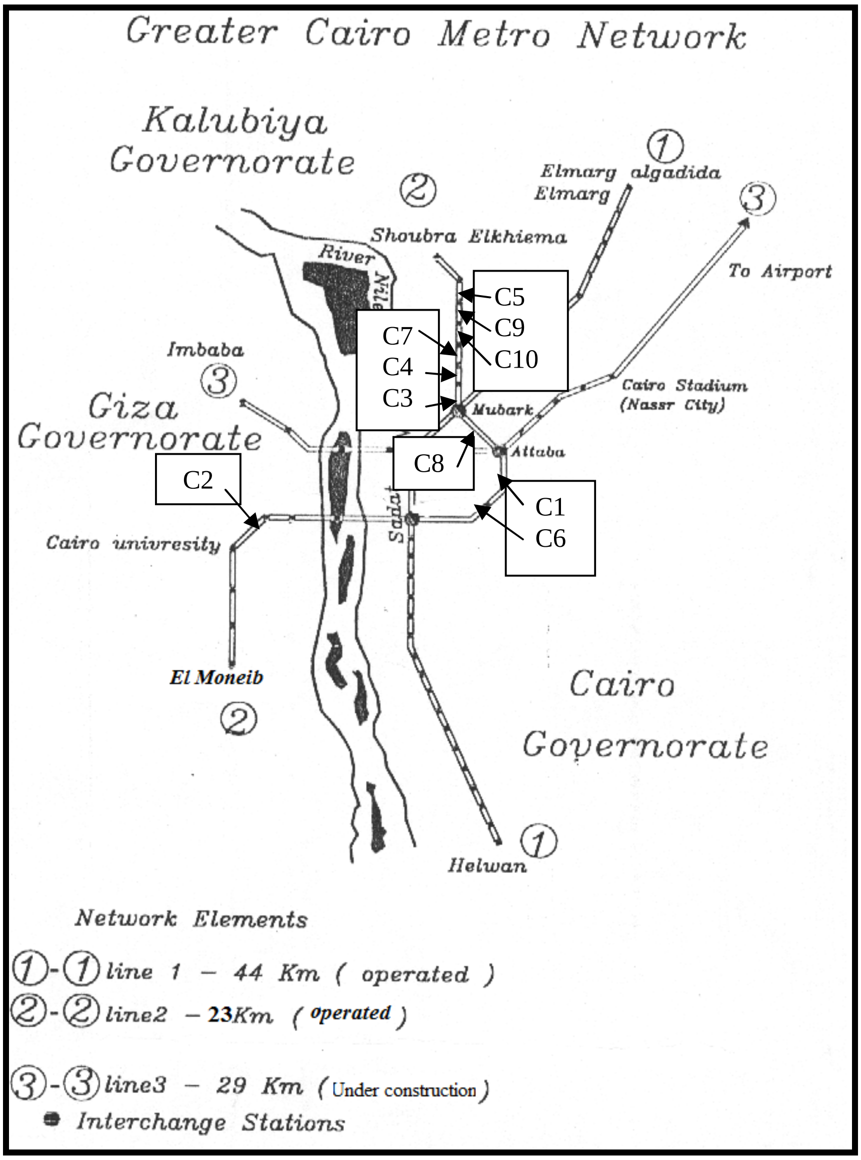

Figure 2: Layout of curves

1.1.2 Permanent Way in Tunnel

The track bed system in the tunnel is different from that used for tracks on ground surface, because the twin block concrete sleepers used here are laid in rubber boots, and are finally embedded in plain concrete bed. To maintain elastic track, microcellular pads (1cm thickness) put in the rubber boots under the bottom of the sleepers. The other components (rails, fasteners, etc.) are the same as used on ground surface. Turnouts used at the main tracks inside or outside tunnel are 1/8 with manganese frogs welded to rails, and laid on wooden sleepers.

1.2 Rolling Stock Characteristics

Weight, dimensions and construction of vehicles greatly affect rail wear, also design of the various suspension systems and axle load are very important.

1.2.1 Description of Running Trains

Trains of six cars, consist of two bogies in every car, were used in the line since the start of operation in October 1996. In the period from 28/10/2000 to 17/2/2001, another two cars were added to every train, thus all trains are running with eight cars since 17/2/2001.

Every car consists of two air sprung bogies from the kind of bolster type. Every bogie consists of two wheel sets with 2.1 m wheel base, and every wheel set consists of two wheels of 860 mm diameter.

1.2.3 Characteristics of Train Wheels

Wheel characteristics affect the rail wear. Thus it is very important to take it into consideration during the study of rail wear phenomenon. Wheels used in line No. 2 follow the standard cross- section R 8 UIC 812.3. However rims of worn wheels have been renewed before reaching the maximum allowable limits of wear. Chemical composition, tensile strength and hardness of wheels are shown in Table 2 and wheel dimensions are indicated in Figure 3 [4].

Table 2: Wheel characteristics

Chemical Composition	C	S	P	M_n	Cr	Ni	Mo	Cu	Si	V
	0.56	0.035	0.035	0.80	0.30	0.30	0.08	0.3	0.40	0.05
Tensile Strength	885 N/mm^2 – 739 N/mm^2									
Hardness (HB)	285 at area of contact									
Wheel diameter (new) (Minimum).	860 mm 790 mm									

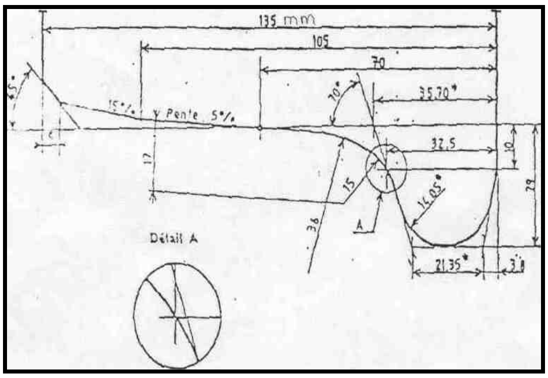

Figure 3: Wheel dimensions of train (Line No. 2)

2. Analysis of Field Measurements of Lateral Rail Wear

Measurements of lateral wear were carried out by the author at selected positions on the outer rails of long and short radii curves which are shown in Table 1. These measurements had been repeated since date of installation on time intervals to follow the lateral wear increase. Using the train operation time table, number of trains operating on the line had been calculated. Table 3 represents an example for the measured lateral wear values and corresponding numbers of trains since the date of rail installation and that were used in the previous study of year 2002.

2.1 Gross loads Calculation

Gross dead and live vertical loads which transmitted from the running trains to the rail have been calculated for the same time of measuring wear.
A survey along an operation day was done to get the actual live loads, thus the total loads are obtained as follows.
Total weight (D+L) of train of six cars = 64.35+ 219= 283.35 tones
Total weight (D+L) of train of eight cars = 85.8+ 277= 362.8 tones
Axles Gross loads = No. of trains * Total weight of train
Wheels gross loads = Axles Gross loads /2
These gross loads (i.e., axles and wheels) corresponding to wear measurements on ten curved tracks are calculated. Table 4 includes an example for this calculation.

Table 3: Measurements of wear at T1, Km 8.800,(El-Attaba-Nagiub)
R=253 m V_1 =65 km/h, V_2 = 50 km/h, Super-elevation = 100 mm
Date of installation: 15/9/1997

Date	Accumulated No. of Trains (6 Cars)	Wear (mm)
02/10/1999	134239	8
12/10/1999	136345	8
27/10/1999	139576	8
23/11/1999	145363	8
09/12/1999	148843	10
26/12/1999	152851	10
15/01/2000	157081	10
27/01/2000	159709	10
22/02/2000	165271	11
22/03/2000	171292	12
27/04/2000	178888	12
16/05/2000	182722	12

Table 4: Accumulated loads corresponding to wear at T1, Km 8.800, (El-Attaba-Nagiub) R = 253 m, e = 100 mm
Date of installation: 15/09/1997

Date	No. of Trains (6 Cars)	Gross Load (Axles)Tones	Gross Load (Wheels)Tones	Wear (mm)	V Km/h	Lub. Or Dry
02/10/1999	134239	38036620.65	19018310.325	8	65	Dry
12/10/1999	136345	38633355.75	19316677.875	8	65	Dry
27/10/1999	139576	39548859.6	19774429.800	8	65	Dry
23/11/1999	145363	41188606.05	20594303.025	8	65	Dry
09/12/1999	148843	42174664.05	21087332.025	10	65	Dry
26/12/1999	152851	43310330.85	21655165.425	10	65	Dry
15/01/2000	157081	44508901.35	22254450.675	10	65	Dry
27/01/2000	159709	45253545.15	22626772.575	10	65	Dry
22/02/2000	165271	46829537.85	23414768.925	11	65	Dry
22/03/2000	171292	48535588.2	24267794.100	12	65	Dry
27/04/2000	178888	50687914.8	25343957.400	12	50	Lub.
16/05/2000	182722	51774278.7	25887139.350	12	50	Lub.

2.2 Relation between Lateral Wear and Gross Loads

Lateral wear of rail is in direct proportion to load transmitted from train wheel to rail head, so it can be represented as:

$$W = k \cdot Q_c \text{ ………. } (1)$$

Where: Q_c = accumulated wheel load

Values of lateral wear of rails "W" and corresponding loads "Q_c" which were recorded for sex curves have been analyzed. Fitting of these points for the six curves are carried out for the records which were taken only before date of lubrication and lowering speed, to get the proportional constant "k" for every curve of them. The parameters which represent these curves and values of "k" are shown in Table 5.

Two curves of 200 m & 210 m radius were lubricated since date of installation, and the lateral wear of their outer rails are small, so they are not taken in the calculations. It has been noticed that super-elevation of the curve of 353 m radius is (25 mm) which is unsuitable for speed of 60 km/h, thus it is not taken in the calculations. Curve of radius 753 ms will not be taken in the analysis as the lateral wear is small (1mm) and constant along the period of survey.

Table 5: Parameters of curves & values of "k"

Curve number	Curve Radius R(m)	Super-elevation (mm)	Design Speed v1 (km/h)	Lowered Speed v2 (km/h)	v^2/R	$W/Q_c = k$
1	200	115	60	50	18	-
2	210	110	65	50	20.12	-
3	223	50	52	50	12.12	$4.30 * 10^{-7}$
4	250	135	70	50	19.6	$11.0 * 10^{-7}$
5	253	90	63	50	15.68	$6.15* 10^{-7}$
6	253	100	65	50	16.7	$6.77* 10^{-7}$
7	253	135	70	60	19.36	$8.0 * 10^{-7}$
8	300	100	71	50	16.8	$7.04 * 10^{-7}$
9	353	25	61	60	10.54	-
10	753	30	80	60	8.53	-

2.3 Relation between Curve Parameters & Lateral Wear of Rail

Analyses have been carried out by the author for points which represent the values of proportional constants " k" and corresponding values "V^2 /R "which are shown in Figure 4, hence a relation between "k" & "V^2 /R " has been obtained at case of dry rails. Thus a relation between wear at dry case and train speed, curve radius, accumulated wheel load has been derived as follows [3]:

$$W_d = (-4.58*10^{-7} + 7.06*10^{-8}\ V^2 /R)\ * Q_c \quad \ldots\ldots\ldots.(2)$$

Also, a mathematical model has been derived for the case of lubricated rails as follows:

$$W_l = (- 5.496*10^{-8} + 8.472*10^{-9}\ V^2 /R\ )\ * Q_c \quad \ldots\ldots\ldots(3)$$

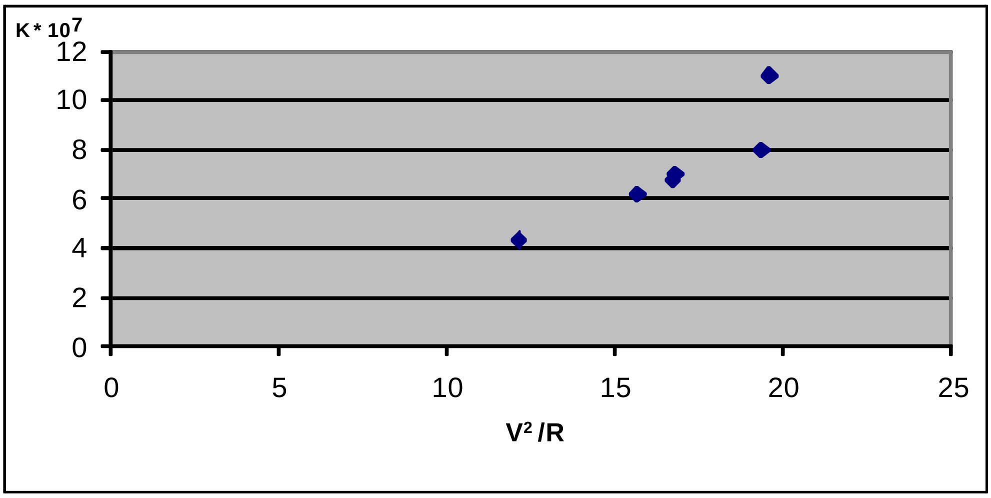

Figure 4: Values of k against V^2 /R

3. Recent Validation for Mathematical Model of Lubricated Curves

Most of Sharp curves from Massara station to Nagieb station were replaced during the period from year 2000 to year 2002; where the lateral wear reached the maximum allowable value (16 mm). Field measurements have been carried out for the lateral wear since the date of installation up till now; however the records of lateral wear for four sharp curves that have been carried out in May 2012 will be used in this item to validate the mathematical model that has been obtained in 2002.

- ***Curve No. 1***

As shown in Table 1, the radius of that curve is 200m. It was lubricated since the date of its installation in 6 July 1999; however it has not been replaced yet as the recorded value in May 2012 was 8 mm (i.e., less than 14 mm).
The calculated gross wheel load in 10 May 2012 equals 134578483 ton.
Substitution in equation 3, the value of calculated lateral wear is 8.194 mm.

- ***Curve No. 4***

This curve was replaced in 6 June 2002 and the operation speed equals 50 km/hour. The accumulated gross wheel load that has been calculated in May 2012 equals 136648620 ton. The obtained value of lateral wear from equation 3 equals 4.07 mm; whereas the measured value is 4 mm.

- ***Curve No. 6***

Replacement of this curve of radius 253 m carried out in first of June 2000. The operation speed is 50 km/hour. The accumulated gross wheel load that has been calculated in May 2012 is 163978344 ton. Substitution in equation 3, the obtained value of lateral wear equals 4.715 mm; whereas the measured value in May 2012 equals 4 mm.

- ***Curve No. 8***

For curve No. 8 in Table 1, the radius is 300 m. The operation speed was raised from 50 to 60 km/hour since date of replacement in 14 June 2002. Thus, the accumulated gross wheel load equals 13664862 in 10 May 2012. The obtained value from equation 3 is 6.382 mm; whereas the recent measured value is 7 mm.

It is noticed from the above carried out calculations after about 10 years, that the derived mathematical model for case of lubrication is still valid; also the error is still less than ±1 mm.

4. General Equation for Rail Lifetime Calculation

German specifications limited lateral wear of rail to be 16 mm, and then the rail must be replaced to avoid derailment [4].
So, substituting $\boldsymbol{W}$ = 16 mm & $\mathbf{V^2/R}$ of any curve in equations 2 & 3 get the gross wheel load Q_c, thus lifetime of rail in years will be:

$$Lt = \frac{2Qc}{365 * n * wt} \text{......(5)}$$

Where:

Lt = Lifetime of rail
n = daily number of trains per direction
wt = weight of loaded train
Q_c= accumulated gross wheel load (i.e., half axle loads)

5. Effect of Design Parameters on Maintenance Cost of Worn Rails

It is explained before that lateral wear results in fast replacing of outer rails in short radii curved tracks, so the effect of design parameters on the maintenance cost of dry and lubricated outer rails of these curves has been analyzed as follows:

The cost of one meter length of dry outer rail in curves of five different radii (R= 200, 225, 250, 300 and 350 ms) have been calculated at cases of different train speeds (V= 50, 55, 60, 65 and 70 km/h), then it has been compared to the cost of the same rail in straight track with age of 30 years which is 333.0 EGP/ one meter. Also, similar calculations have been run for the same curves at the same mentioned speeds to get the cost of one meter of curved rail at case of lubrication, as shown in Table 6, using the following collected data [6]:

Rate of grease consumption per day / one train = 0.25 liter.
Total No. of operating trains / day = 27
No. of tracks = 2
Length of short radii curved tracks = 1322.2 m / one track
Price of one liter of grease = 20.0 EGP
Period of comparison = Age of straight rail
= 30 years

No. of replacing dry rails (S_d)
No. of replacing lubricated rails (S_l)

Table 6: Maintenance cost of worn rails in curves compared to straight rails

R (m)		V= 50 km/h			55 km/h			60 km/h			65 km/h			70 km/h		
		Lt (years)	S	Cost/ m	*Lt* (years)	S	Cost/ m	*Lt* (years)	S	Cost/ m	*Lt* (years)	S	Cost/ m	*Lt* (years)	S	Cost/ m
200	dry	2.84	10.56	3516.48	1.98	15.14	5041.62	1.49	20.13	6703.29	1.17	25.66	8544.78	0.95	31.57	10512.81
	lub.	23.65	1.261	978.92	16.5	1.82	1165.07	12.42	2.42	1364.87	9.74	3.08	1584.68	7.91	3.79	1821.08
225	dry	3.7	8.1	2697.3	2.46	12.2	4062.6	1.8	16.67	5551.11	1.39	21.54	7172.82	1.12	26.8	8924.4
	lub.	30	1	892.01	20.5	1.46	1045.19	15	2	1225.01	11.58	2.59	1421.48	9.33	3.21	1627.94
250	dry	4.87	6.16	2051.28	3.05	9.84	3276.72	2.16	13.87	4618.71	1.64	18.25	6077.25	1.31	22.98	7652.34
	lub.	30	1	892.01	25.42	1.18	951.95	18	1.67	1115.12	13.67	2.195	1289.94	10.91	2.75	1474.76
300	dry	9.27	3.23	1075.59	4.76	6.3	2097.9	3.1	9.66	3216.778	2.25	13.31	4432.23	1.74	17.26	5747.58
	lub.	30	1	892.01	30	1	892.01	25.83	1.16	945.29	18.75	1.6	1091.81	14.5	2.07	1248.32
350	dry	26.1	1.15	382.95	7.94	3.78	1258.74	4.5	6.67	2221.11	3.06	9.8	3263.4	2.28	13.2	4395.6
	lub.	30	1	892.01	30	1	892.01	30	1	892.01	25.5	1.2	958.61	19	1.58	1085.15

Results of that economic study are plotted in Figure 5, where it is obvious that increasing curve radius for the same speed decreases cost of rail maintenance, but increasing train speed results in high significant values of maintenance cost. The maintenance cost of track with 300 m radius and train speed 50 km/h in dry case is nearly equal to the maintenance cost of track with the same radius and train speed 65 km/h in lubricated case. Also, in case of curve with radius equals 350 m and train speed equals 50 km/h, cost of dry curved rail approaches the same cost of straight rail, whereas it is less than the cost of using lubricant.

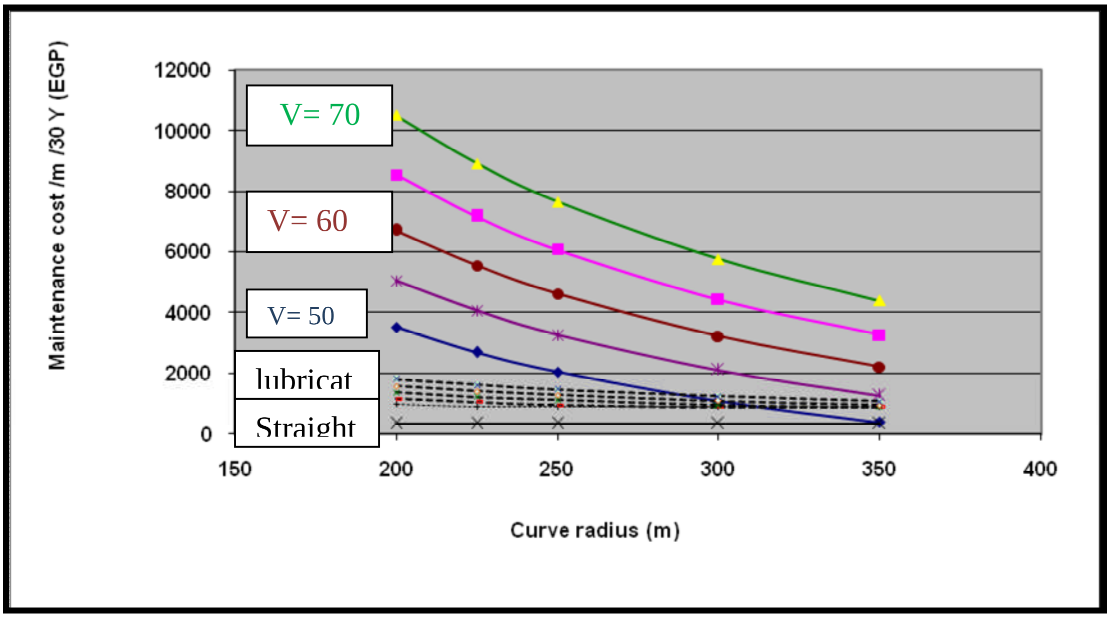

Figure 5: Effect of design parameters on maintenance cost/m/30 years (EGP).

6. Conclusions and Recommendations

The main conclusions which have been achieved in this study could be represented as the following:

- The mathematical models that have been obtained by the author in year 2002 for calculation of lateral rail wear of sharp curves of Cairo metro line 2 are still valid to be applied for Cairo underground metro lines as they have the same characteristics. Also the accuracy is still in the range of ±1mm. Regarding other railways with different characteristics such as Egyptian National Railways; the obtained mathematical models cannot be applied due to different parameters of bogies and curves` radii.
- Lateral wear of the outer rail in suburban curved tracks is affected greatly by choosing the design parameters which are used for these curves. Therefore, lifetime of rail which is dependent on the value of the lateral wear is also affected greatly by the magnitudes of these parameters.
- *Effect of curve radius*

Curve radius affects lateral wear and lifetime of rail in an inverse proportionality (**W** α **1/R**). Lateral wear can be reduced by increasing curve radius, thus lifetime of rail can be increased and rail cost will be minimized.

- *Effect of train speed*

Train speed plays a serious role in occurrence of lateral wear of rail, where the value of lateral wear is in direct proportion with the squared value of train speed (**W α V**^{2}). It is obvious from the cost analysis that, for curves of radii 200, 225, and 250, when train speed is 70 km/h; rail cost (in time span of thirty years) approaches three times the rail cost in case of speed 50 km/h for the same curve radius.

- *Effect of super-elevation*

Super-elevation deficiency is in direct proportion with lateral wear of rail, thus it reduces the lifetime of rail especially in short radii curved tracks. Increasing super-elevation deficiency results in increasing non compensated force on the running edge of the outer rail; thus lateral wear increases rapidly.

- *Effect of lubrication*

Lubrication of wheel flange and respectively the rail head has a great effect on lifetime of rail, as when these curves are lubricated, the lateral wear is reduced to 12 % in comparison with the dry case. Thus, lifetime of rail is increased to eight times the lifetime of rail in the dry case.

- *Rail cost (at time span of thirty years)*

Rail cost (at time span of thirty years) is minimized when curves are lubricated. At case of curve lubrication, rail cost comes down to a range of (17 % - 25%) when train speed is 70 km/h.

The following recommendations which contribute in reduction of the high levels of lateral wear of rail have been introduced as follows:

- It is recommended for new lines with trains with no lubricators, that track alignment should choose bigger curve radius; more than 350 m is preferable, to avoid excessive curving wear, hence the maintenance cost will be reduced.
- The track alignment should choose suitable train speed which agree with the designed super-elevation and curve radius. Also, high train speeds on short radii curves are not recommended in order to reduce rail maintenance costs. Speed on short radii curves is not preferable to be more than 60 km/h.
- If it is necessary to use curves of radii less than 350 m when train speed is equal or greater than 50 km, lubrication of wheel flange should be used to minimize lateral wear and rail costs.

References

1- Ministry of Transport, “Greater Cairo Transport Study”, 2011.

2- Ahmed A. Khalil, Assessment of noise levels in tunnels and on ground surface for Greater Cairo metro network, Master thesis, Faculty of Engineering, Cairo University, 1998.

3- Ahmed A. Khalil, The effect of different design parameters of suburban curved tracks on wear and lifetime of rails, PhD thesis, Cairo University, 2002.

4- National Authority for Tunnels, As built drawings of railway tracks for Cairo metro line 2, 1997.

5- The Egyptian Company for Maintenance and Operation of Cairo Metro, Track Engineering Department, Rail wear periodical measurements, 2012.

6- National Authority for Tunnels, Bill of quantities (BOQ) of track-works, 2010.