Determination of the Economic Radii of Horizontal Curves for Suburban Railway Tunnels

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Abstract

Railroad of subways are usually constructed along narrow streets, either in tunnels or on ground surface, to avoid any settlements of the neighboring structures. Hence it includes several short radii curves. All previous railway practices agreed that running of trains on these curves resulted in excessive rail wear due to abrasion action of wheels, specially on the outer rail. This Phenomenon leads to high maintenance cost, thus this paper studies a new method for determining the suitable radii of horizontal curves used in alignment of railway tunnels regarding minimum cost.

1. Introduction

Subways are considered the backbone and the most important urban transportation mean in comparison with the other inner-city networks, as they contribute in solving traffic congestion, not only in the heart of the megalopolises but also in many places in greater urban areas.

Nowadays, the ministry of transport in Egypt intends to complete construction of the Greater Cairo Metro Network because of the greater demand of passengers, where 12.5 % of Greater Cairo residents use the network daily in their transportation. 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.

Rail is the most important component in the permanent way, as it is the member that is in direct contact with running train wheels and it distributes loads on sleepers. In addition it is more expensive. Wheel /rail contact results in many serious phenomena such as air-born noise, vibrations, rail wear and rail corrugations. Rail wear is the most important reason for replacing rails in subways, especially in Tunnels of short radii curves such as in some sections of Line No. 2 of Greater Cairo Metro Network, so this paper studies in detail how to obtain the economic radii of horizontal curves used in the alignment of railway tunnels.

2. Problem Definition

Execution of suburban metro networks are considered the principal projects for the upgrading of the public transport system in greater cities. The permanent way of these networks includes long distances of short radii horizontal curves, therefore wear phenomena always occur at both rails and train wheels.

Studying of this phenomenon became very necessary because of its bad and decisive effects on wheels and rails of the curved tracks that lead to excessive costs of maintenance and replacing rails. This phenomenon is very clear in the curved tracks of Greater Cairo Metro Network; especially in Line No. 2. The following item exhibits a plan for that network.

2.1 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 [1]. This network includes three different lines as shown in Figure 1.

2.1.1   Line No.1

It is considered the backbone of the metro network, as it extends from Helwan in the south through the city center in a tunnel, to El-marg in the north. Its length is 42.5 km, and carries approximately 30 % of the total volume of public transport in Cairo, moving between 35 stations along the line.

2.1.2   Line No.2

This line extends from Shubra El-kheima area on the surface, crossing the Ismaillia canal in a tunnel to extend through Sahel Rod El- farag and Shubra areas, crossing Ramses square to Tahrir square under the first line. The line passes under the two branches of the Nile river towards Dokki square, to Boulak El-dakrour under the railway lines of the upper Egypt route . It extends southward parallel to Egyptian national railways on the surface to the terminal station (Giza suburban). Nowadays two other stations are added to the line to terminate at El-Monib. Total length of the line is 22 kms including 20 stations.

2.1.3 Line No.3

As mentioned in the study which was carried out in 1973 [1], it was proposed to connect Embaba to El-Darrasa. This line is under recent studies, as it is recommended to extend till Cairo airport in the north east of Cairo.
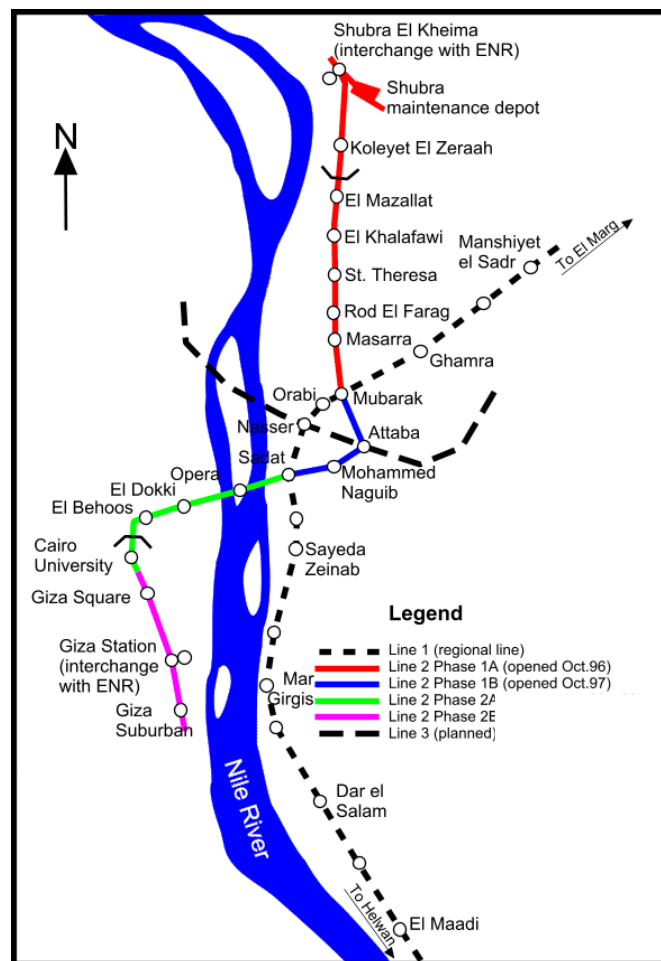

Figure 1: Greater Cairo Metro Network

2.2   Train Movement in Curved Sections

When the vehicles move on a curved track, both the outer wheels slide on the rail in the direction of movement and both leading wheels slide laterally. Therefore the outer leading wheel slides longitudinally and laterally with respect to the rail.

The two wheels on the front axle of a bogie tend to run in a straight direction where the outer wheel flange crowds hard against the rail and it tends to roll on the fillet or side of the flange and lifts the tread from the rail.

At design speed, the outer front wheel sometimes rolls on the fillet or side of the flange, with the tread lifted clear of the rail, for long distances. The path of contact of the inner wheel with the rail is a zigzag line which produces vibrations [2]. This vibration sometimes sets up a ringing sound the squealing of a pig, but varies in pitch all the way from a coarse, grating sound to a howl, and up to sharp or shrill ring. This vibration resulted by the rapid alternate catching and slipping of wheel-tread in contact with the rail.

The fact, then, that the outside wheel acts against the side or corner of the outer rail head by flange pressure, while the inside wheel acts against the inner rail only by sliding friction between tread and rail top [3]. The rail head serves as running surface and guide element so it is subjected to wear.

The vertical and lateral forces (wheel loads, guide forces, acceleration and braking forces) which act through the wheel on the rail resulting in high dynamic stresses and lead to plastic deformations and wear of the rail head.

This wear leads to reduction of the profiles of wheel and rail and change at the circumferences of them as compared to new profiles as shown in Figure 2.

In addition to the bad effects of wear at the running rails, this phenomenon leads to several bad and decisive influences on the whole track-system and adversely affect the running quality and derailment safety [4].

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

2.3   Influences of Rail Wear on the Track System

Wear of rail leads to several bad effects on the train movement as well as on the track economy. Some of these effects can be summarized as follows:

1. Rebounding of train wheels on the rails which leads to derailment [5].

2. Increasing the wave length of train oscillations on track, hence increasing the lateral acceleration and affecting badly on comfort of passengers [6].

3. Decreasing the lifetime of rails, hence increasing the cost of maintenance.

4. Rising the rolling and curve noises to higher levels which leads to more environmental dangerous effects on human body [7].

5. Wear leads to loose the track components as a result of high vibrations, hence increasing maintenance cost [8].

3. Field Measurements

The rapid increase of rail wear in Line No. 2, especially on short radii curves, puts this phenomenon under the investigation by the Operation Authority of Greater Cairo Metro Network. After short period from staring operation of the line, numerous measurements of the outer rail head wear had been started periodically to avoid train derailment.

The records, the huge collected data of the rail head wear, and its relation with the number of trains are used to analyze the wear phenomenon in detail to determine the effect of different design parameters of curved track on wear and lifetime of rails, hence, the suitable minimum radius of tunnel can be determined for the next projects.

3.1 Relation between Tunnel Curve Radius & Wear of Rail

Analysis of wear records had been carried out for Line No.2 taking into consideration the parameters affecting strongly lateral wear of rail. Thus the analysis concentrated on train speed, curve radius, accumulated wheel loads and the coefficient of friction. The following mathematical models had been derived [9].

- For case of dry rails

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

-For case of lubricated rails

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

Where:

W_d : lateral wear of rail in curved tunnels at case of dry.

W_l : lateral wear of rail in curved tunnels at case of lubrication

V^2 : train speed in km/h

R: radius of track in meters

Q_c : cumulated wheel load

3.2 General Equation for Rail Lifetime Calculation

Specifications have limited lateral wear of rail to be 16 mm, then the rail must be replaced to avoid derailment.

So, substituting W = 16 mm & V^2/R of any curve in the previous equations to get the gross wheel load Q_c, thus lifetime of rail in years will be [9]:

$$Lt = \frac{2Qc}{365 * n * wt}$$

Where: **Lt** = *Lifetime* of rail
   n = daily number of trains per direction
   wt = weight of loaded train
   Q_c = accumulated wheel load

4. Optimization of the Economic Short Radii Curves of A railway tunnel

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 will be 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 kms/h) compared to the cost of the same rail in straight track with age of 30 years which is 138.89 EGP/ one meter. Also the same 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 using the following collected data:

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 = 3 EGP

Period of comparison = Age of straight rail = 30 years

Grease cost / one meter of curved rail = (0.25 * 27 * 3 *30 *365) / (1322.2 * 2)

$$= 83.85 \text{ EGP}$$

No. of replacing dry rails (S_d) = 30 / lifetime of dry rails

No. of replacing lubricated rails (S_l) = 30 / lifetime of lubricated rails

Cost / m (dry rail) = S_d *138.89 EGP

Cost /m (lubricated case) = S_l *138.89 + 83.85 EGP

Results of this economic study are shown in the following table, and have been plotted also in figure 3. 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. It is indicated that cost/ m at case of curve radius = 340 m and train speed = 50 km/h equals 210.75 EGP for dry case, but for the same curve with the same parameters at lubricated case; the cost/m equals 222.8 EGP. Also, at case of curve with radius R = 350 m and train speed V= 50 km /h, cost of dry curved rail approaches the same cost of straight rail [9].

| R (m)		V= 50 km/h			55 km/h			60 km/h			65 km/h		
		Lt (years)	S	Cost/ m	Lt (years)	S	Cost/ m	Lt (years)	S	Cost/ m	Lt (years)	S	C
200	dry	2.84	10.56	1467	1.98	15.14	2103	1.49	20.13	2796	1.17	25.66	3
	lub.	23.65	1.261	282.5	16.5	1.82	336.6	12.42	2.42	419.96	9.74	3.08	5
225	dry	3.7	8.1	1126	2.46	12.2	1694	1.8	16.67	2316	1.39	21.54	
	lub.	30	1	222.75	20.5	1.46	286.6	15	2	361.63	11.58	2.59	4
250	dry	4.87	6.16	856	3.05	9.84	1366.5	2.16	13.87	1926.5	1.64	18.25	
	lub.	30	1	222.75	25.42	1.18	247.7	18	1.67	315.8	13.67	2.195	3
300	dry	9.27	3.23	449	4.76	6.3	875.5	3.1	9.66	1342	2.25	13.31	1
	lub.	30	1	222.75	30	1	222.75	25.83	1.16	245	18.75	1.6	
350	dry	26.1	1.15	160	7.94	3.78	525	4.5	6.67	926	3.06	9.8	1
	lub.	30	1	222.75	30	1	222.75	30	1	222.75	25.5	1.2	2
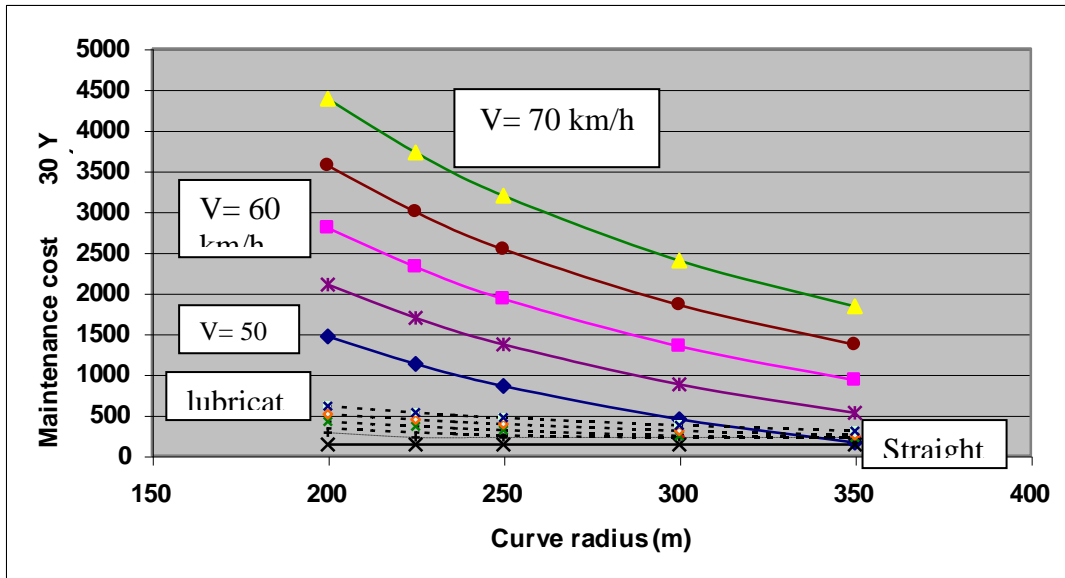
Figure 3 : Effect of design parameters on maintenance cost (EGP).

5. Conclusions and Recommendations

The general conclusions derived from the analysis and results, also recommendations for choosing the suitable radii of curved railway tunnels are as follows:

• 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.

• Train speed plays a serious roll 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 V²**). It is obvious from the cost analysis that when train speed is 70 km/h, rail cost (in time span of thirty years) is three times the rail cost at case of speed 50 km/h for the same curve radius.

• It is recommended for new lines with trains with no lubricators, that alignment should choose bigger curve radius; more than 350 m is preferable, to avoid excessive curving wear, hence the maintenance cost will be reduced.

• 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 cost.

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