Technical-Economical Evaluation of Chain Vertical Alignment in Underground Urban Subways: The Case of Qom Subway, Line A

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Abstract

Urban subways are one of the main parts of urban transportation networks in every city that always requires much attention in order to improve its efficiency in aspects of safety, reliability speed and costs. As the viewpoint of costs, an accurate design, especially design of vertical alignment, can have a dominant role to reduce the costs of urban railway projects. This paper seeks to evaluate the advantages and disadvantages of designing chain vertical alignment for urban subways in compare to flat vertical alignment. To achieve this goal, line A of Qom subway in Iran was selected as a case study in this research. Five parameters considered in the technical-economical evaluation: (1) energy consumption, (2) rolling stock, (3) operation, (4) civil works and geotechnical and (5) hydrological, drainage and pumping. According to the results, a power saving of about 40% have been estimated in the chain vertical alignment for the train without regenerative braking in compare with the flat vertical alignment, although the power saving was calculated less than 10% for the train with regenerative braking. Finally it was found that due to the modern rolling stock technology, the chain vertical alignment represents fewer advantages in compare to the past years.

Keywords : *Urban underground subway, Chain vertical alignment, Power supply saving, Construction costs, Technical-economical evaluation*

1. Introduction

Urban railways and especially heavy underground rail transits are one of the main parts of transportation system of each city and usually transfer thousands or even millions of passengers daily in metropolitans such as Tokyo, London and New York. Due to this high percent of daily transports, rail industry generally is one of the biggest costumers of energy. For instance in the Great Britannia, traction alone consumes almost 670 million liters of diesel and 3000 GWh of electricity annually that its expenditure is more than £500 million (Puri 2012). Besides of the train traction, many other parameters such as braking, weight of the train and the condition of line effect on the consumption of operation energy in the urban rail transportation (Haidong *et al*. 2007). Since the railway network play a key role in the economy of each country, the energy saving is receiving more and more attention and it is becoming a significant issue in their economy (Xiong *et al*. 2012). On the other hand, construction costs of underground railway projects and establishing new tracks also are considerable. Thus, it is essential to reserve more attention to reduce railway costs in aspects of energy and construction. Designing phase could be so important to reduce the costs of railway projects.

This paper studies the advantages and disadvantages of chain vertical alignment in compare to flat vertical alignment, which are two common types of vertical alignment in subways, by evaluating their technical-economical features. Line E in Paris, Cairo L3 and Hanoi MRT3 are some examples of chain vertical alignments for urban subways. The diagrams of these two different types of vertical alignment have been shown in Fig. 1. The largest portion of energy consumption in railway operation is constituted by the energy consumed for running train cars

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Table 1. Main Technical Characteristics of Qom subway, Line A

Characteristics	Figure
Length	14 km, underground
PPHPD	23250 at peak hour (horizon 2036)
Headway	150 seconds
Number of Stations	14, all underground
Interchange Stations	1 at A9 station with Qom Monorail
Platform Length	100 m
Maximum Design Speed	90 km/h
Maximum Operation Speed	80 km/h
Power Supply	3rd rail – 750Vdc

that is about 70% of the total energy consumption (Ogasa 2008). Thus based on the Fig. 1 due to the specific design of chain alignment, a reduction of energy can estimate for this geometry in compare to flat alignment. These longitudinal profiles considered as proposed options regarding the vertical alignment of Qom subway line-A in Iran and a comparison have conducted to choose the best vertical alignment between two adjacent station for the project. In order to reach comprehensive results for proposed options of Qom subway line A, technical-economical evaluation included five factors of (1) energy consumption, (2) rolling stock, (3) operation, (4) civil works and geotechnical and (5) hydrological, drainage and pumping. Table 1 illustrates the characteristics of Qom subway line A.

2. Literature Review

Both of the energy and transportation are one of the fundamental elements of economic development for each country and the energy consumption takes up a large part of railway transportation cost (Yinping *et al*. 2009). Due to this significance of the issue, many researchers have conducted studies to find and present possible ways for reducing the costs in rail transportation. The main purpose of some researchers were to present new methods for improving the system of trains as the point of electric power and energy saving (Xiong *et al*. 2012; Yinping *et al*. 2009; Haidong *et al*. 2007; Adinolfi *et al*. 1998; Bocharnikov *et al*. 2007; Alleger *et al*. 2010). Electrified systems of urban subway lines always involve considerable power demand levels (Adinolfi *et al*. 1998). Miyatake and Ko (2009) conducted a research of optimization of train speed to minimize the energy consumption. Also, Feng (2011) presented another research for optimizing of target speeds of express railway trains to save the traction energy. The other side of reducing costs is optimizing the geometric design and vertical alignment. Generally, designing of project level and vertical alignment in railway projects depends on the experience of designer and an inaccurate
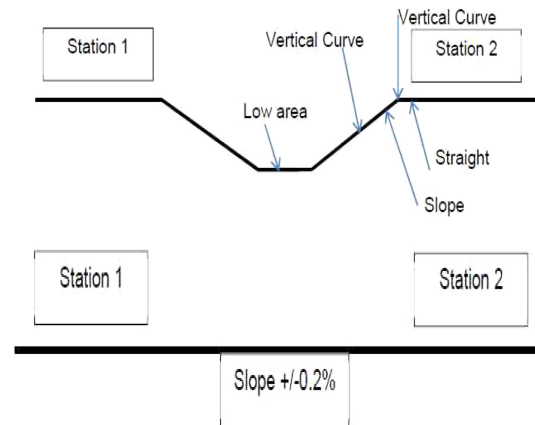

Fig. 1 (above): Chain vertical alignment
(below): Flat vertical alignment

design could considerably impact on construction costs (Bababeik and Monajjem 2012). The recent study was done by Bababeik and Monajjem (2012) recommended a new program to investigate the best vertical alignment for a track and optimizing the design. Bababeik and Monajjem (2012) recommendation model was validated on a real track and it was found that their model can be exerted to find optimal vertical alignment in railways. Some researchers tried to change the profile of subway tunnels. Ruelland and Al-Haddad (2006) studied the optimization of subway tunnel profiles by using genetic algorithms and simulation. Their research recommended following steps in order to saving the energy: (1) optimizing the profiles for the best running time and (2) reducing the speed of trains while meeting the required line capacity criteria. Another research was conducted by Ghanbarpour (2013) to investigate the optimum of internal diameter for circular subway tunnels in Iran. Ghanbarpour (2013) compared the construction cost of different tunnel diameters with operational and maintenance cost including delay time of passengers due to limited speeds as a result of limited dynamic envelope of wagons, tear cost of wheels and rails, and consumed power of vehicle during a 30-year life cycle.

3. Data Evaluation and Discussion

In this section a comprehensive evaluation of designing chain vertical alignment for subways have been conducted. As it mentioned before, the technical-economical evaluation was studied from several points of view that are: energy consumption, rolling stock depreciation, operation and maintenance, civil works, and hydrological.

3.1 Energy consumption

This section describes the potential energy savings that could be made by designing the chain vertical alignment. The presented calculation is based on experiences of Iranian operational organization and rule of thumb calculation for consumption of traction power that is very close to the simulation results. Some assumptions were considered in the evaluation: (1) inter-station of 1000 m which corresponds to Qom's context with a line of about 14 km and 14 stations, (2) assumed grade of 4% on 300 m from end of each station (600 m for the whole inter-station), (3) maximum operating speed of 80km/h, (4) acceleration rate of 1 m/s² (as Qom's rolling stock parameter). It should be mentioned that the maximum of vertical grade for subways is 4% in Iran.

The evaluation of energy consumption is classified in two different cases: (1) without regenerative braking and (2) with regenerative braking. The consumption of traction power in the case of without regenerative braking for chain vertical alignment was calculated 12 kWh, while it is estimated 20 kWh for the flat vertical alignment. Thereby, track chain vertical alignment ensures a power saving of about 40% in compare to flat vertical alignment. But the modern rolling stocks are using regenerative breaking , so they typically can regenerate 45% of the power used in traction mode and there is enough energy users in traction phase while they are in braking phase. Considering the above estimation, we can deduce the results as the following sub titles:

3.1.1 Flat vertical alignment

45% of the original value (20 kWh, case of without regenerative braking) could be reduced due to regenerative braking train. $0.45 \times 20 = 9$ kWh. So, this gives a traction consumption of $20 - 9 = 11$ kWh for the considered inter-station.

3.1.2 Chain vertical alignment

The track vertical alignment with a lower mileage point does not encourage the electrical regeneration; the mechanical braking is applied at the end of the slowing down running phase when the electrical braking is not efficient anymore. In that phase, the remaining kinetic energy of the train is at its lowest level (between 40 km/h and 0 km/h, the electrical braking represents only 25% of the electrical regenerative capacities). From 12 kWh originally required in traction, about 2.25 kWh (~18%) could be saved due to regenerative braking. This gives a traction consumption of $12 - 2.25 = 9.75$ kWh. Therefore the saving is only around 10% in compare to a flat vertical alignment by considering a 4% ramp.

3.1.3 Comparison of flat and Chain alignments

Regarding above discussions, energy consumption for flat vertical alignment was calculated 11 kWh in the case of regenerative braking, while it is 9.75 kWh for chain vertical alignment. Therefore, an energy saving of about 10% could be expected in the case of chain alignment, with the grade of 4%. Moreover in the chain alignment proposed for Qom subway line-A, the grade on the main line never reaches 4% and it is mainly less than 2%, except in the last two inter-station where the grade reaches 2.5%. Considering these points, it can be assumed that the energy saving with track chain vertical alignment and by using the regenerative braking could be even less than 10% for this project, if the vertical alignment has a chain form over whole its length. Thus, due to the modern rolling stock technology, the chain vertical alignment does not represent considerable advantages in compare to the flat alignment.

3.2 Rolling stock depreciation

The type of the track longitudinal profile does not have strong impacts on the rolling stock. The braking system is mainly electrical and the mechanical braking system is applied only from 5 km/h to full stop. Consequently, the mechanical braking system is applied in the station areas and it does not make any differences in both of cases. The interests of designing based on the chain alignment were very valuable in the past years, when the mechanical braking system was applied from 30 km/h to 0 km/h but nowadays with the modern rolling stock, most of the braking is done electrically to encourage the regeneration. Savings on brake pads and disc / wheel wear and tear is not anymore an issue.

It should be noted that other components of vehicle could be also effective but, they are not so important as much as the braking system in the evaluation.

3.3 Operation and maintenance

The chain vertical alignment has no impact on the daily operation of the line. The main operational characteristics of the line, such as the commercial speed, running trip time, headway, etc will not strongly impacted by flat or chain alignment. However, from the point of operation and maintenance organization, having dewatering posts at low point will require specific maintenance care and staff. This may slightly increase the overall operating and maintenance costs.

3.4 Civil works and geotechnical

3.4.1 Soil characteristics and geotechnical parameters
If the soil is not enough suitable for digging/boring a

tunnel at upper layers, one solution could be to dive deeper between stations, in order to reach soil with better characteristics. The opposite situation can also happen: in order to avoid inappropriate soil layers located at deeper levels, the tunnel can be deviated to upper layers to avoid unsuitable soils. In the case of Qom subway, the soil characteristics do not vary significantly in deeper positions, therefore there is no justification to select a chain vertical alignment for the reason of geotechnical characteristics. For a chain vertical alignment, special reservoirs under the track superstructure should be arranged for collecting the drained water, at the lowest point.

3.4.2 Rail level impact

The chain profile has the following properties:

(1) As the tunnel overburden is quite low, around one TBM diameter, the chain profile allows to keep the rail level in station and consequently the platform at a shallow level and to quickly increase the tunnel overburden for safer tunneling.

(2) If the tunnel overburden is deemed sufficient, the chain profile allows to raise the rail level in station and thus increase the trip attraction of the station by decreasing the height that the passengers have to walk up or down. On the other hand, the construction costs of station are significantly decreased.

Here we can mention some examples of chain vertical alignment shown of the existing Qom subway vertical alignment. The examples are the following:

- For a very short inter-station (300 m), we get a maximum increase of overburden of almost 3 m.

This value is reached by setting at the end of the station a grade of 3.4% with a minimum radius of 1600 m for circular transition curve, then by keeping this grade of 3,4% for a minimum length of 20 m (length of a car), then a transition curve with a minimum radius of 1600 m for setting a 1% grade (down) connected to a 1% grade (up) by setting a circular transition curve with a minimum radius of 1600 m. The same curves are set on the second half of the inter-station.

This curve arrangement which is shown on the drawing hereunder is slightly different because the curves are not strictly symmetric due to the fact that both stations are not exactly at the same level. The vertical alignment is the following:

◦ Transition from horizontal to 3.4% =54.4 m,
◦ Grade 3.4% =20 m,
◦ Transition from 3.4% to 1 %= 38.4 m,
◦ Grade 1% = 20 m,
◦ Transition from 1% down to 1% (up) =32 m,
◦ Total for one half of the vertical alignment = 150 m

OK for minimum inter-station 300 m

- For a rather long inter-station (1100 m) we get an increase of depth of 7 m. See drawing here under In that case, we did not try to get the maximum depth. It is only an example of a reasonable deepening of the vertical alignment to obtain a better o verburden for tunnel or to raise rail level in stations (for the last case, it would be wise to raise track level in stations for about 3 m in order to keep a reasonable overburden for tunnel in approach of stations).

• It has to be noted that the transition curve starts at the end of the platform, not at the end of the station.

• Furthermore, the vertical transition curves cannot be superposed with horizontal transition curves or turn-outs (for instance in crossovers).

3.5 Hydrological, drainage and pumping

Chain vertical alignment induces a pumping chamber to be implemented at the lowest point. Drainage pipes will be required to send back the wasted water to the station if no direct throw could be done at the lowest point. Also reservoirs should be arranged under the track superstructure to collect and store the water (infiltration, washing, etc). This will induce the following:

- increased Investments cost of the Project;

- Monitoring of this equipment which will require maintenance activities and staff during operation.

- In addition the dewatering station shall be electrically powered from 2 independent sources, which will require a feeding from the adjacent LPSs. This will also induce extra costs to the overall project.

The pumping chambers can be installed in a recess and water is pumped up to the station or to surface as shown on the drawing here under. As a matter of fact, water leakage is very low in bored tunnel as well as in conventional tunnel clad with an external watertight membrane. A value of 1 lit/day/m² of lining are commonly taken. A leakage of 1, 88 lit/m/day from stand pipe (water pipe for firefighting) has to be added. In any case pumping chambers and reservoirs under the track superstructure are required at the low points. Construction cost and maintenance of these pumping chambers and installations are important issues to be considered in the concept and decision about the vertical alignment.

4. Conclusion

This paper evaluated the features of designing chain vertical alignment for the Qom urban subway as a case study. Results of this technical-economical evaluation are deduced as the following.

By modernization of subway systems, advantages of designing a chain vertical alignment in compare to a flat vertical alignment for subway systems are significantly decreasing and so, a chain form alignment is no more recommended as it was before. Concerning Qom subway line A, as a result of the above mentioned sections, there is not any advantage for a chain vertical alignment from geotechnical, civil work, and operation points of view. Although a small saving about 10% on energy consumption could be expected in the case of chain vertical alignment, but additional expenses for construction and especially implementation and maintenance of drainage and pumping facilities will be generated in this case.

Finally, as the chain vertical alignment brings more constraints during the works execution and is not an economical concept, it was not recommend for new urban subway with regenerative rolling stocks.

5. Further Studies

Further studies are recommended to conduct a similar evaluation for other lines in order to compare the results. Also, some other parameters such as the impact of other parts of vehicle and infrastructures on the operation and construction costs can be added to the evaluation in future studies.

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