Araştırma *Tuncar&Kıyak/Kırklareli University Journal of Engineering and Science 7-2 (2021) 205-220*

DOI: 10.34186/klujes.944183 *Geliş Tarihi:28.05.2021* *Kabul Tarihi:12.07.2021*

ECONOMIC ANALYSIS OF MAGLEV TRAIN TECHNOLOGY: A CASE STUDY FOR ANKARA-SIVAS LINE

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Abstract

Population density has been rapidly shifting from rural areas to city centers. The increase of population in cities brings transportation problems with it. Conventional public transportation is not enough to solve these problems. One of the alternative transportation methods developed for this matter is maglev train transportation. Maglev train km-passenger transport rates reveal that this technology provides per capita environmental contribution. Maglev trains have various advantages over conventional trains. Since there is no contact with the guide track, there is no friction. It is less noisy and faster than other trains. In this study, the application for a maglev train line Ankara-Sivas in Turkey. That can be applied in the economic analysis was conducted for four different versions. According to the analysis, version 1, which has 2.1% more cost considering the number of wagons, but which has twice the number of wagons of the alternative version and has 4 stations with 0.5% more cost considering the number of stations, was found suitable.

Keywords: EMS, Guideway, HSR, Maglev Economics, Maglev Train

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DOI: 10.34186/klujes.944183 *Geliş Tarihi:28.05.2021* *Kabul Tarihi:12.07.2021*

MAGLEV TREN TEKNOLOJİSİNİN EKONOMİK ANALİZİ: ANKARA-SİVAS HATTI İÇİN BİR DURUM ÇALIŞMASI

Öz

Nüfus yoğunluğu hızla kırsal alanlardan şehir merkezlerine kaymaktadır. Şehirlerde nüfus artışı beraberinde ulaşım sorunlarını da beraberinde getiriyor. Konvansiyonel toplu taşıma bu sorunları çözmek için yeterli değil. Bu konuda geliştirilen alternatif ulaşım yöntemlerinden biri de maglev tren taşımacılığıdır. Maglev tren km-yolcu taşıma oranları, bu teknolojinin kişi başına çevresel katkı sağladığını ortaya koymaktadır. Maglev trenlerinin geleneksel trenlere göre çeşitli avantajları vardır. Kılavuz ray ile temas olmadığı için sürtünme yoktur. Diğer trenlere göre daha az gürültülü ve daha hızlıdır. Bu çalışmada, Türkiye'de bir maglev tren hattı Ankara-Sivas uygulaması. Ekonomik analizde uygulanabilen dört farklı versiyon için yapılmıştır. Yapılan analize göre, vagon sayısına göre% 2,1 daha fazla maliyeti olan, ancak alternatif versiyonun iki katı vagon sayısına sahip olan ve istasyon sayısına göre% 0,5 daha fazla maliyetle 4 istasyona sahip olan versiyon 1 uygun bulunmuştur.

Anahtar Kelimeler: EMS, Kılavuz Yolu, HSR, Maglev Ekonomisi, Maglev Treni

1. Introduction

In 2050, 68% of the world's population is expected to live in city centers [1]. Population density is rapidly shifting from rural areas to city centers. The increase of life in cities brings transportation problems with it. Many different transportation alternatives have been developed to solve this problem, which has been increasing for years. One of them is maglev train transportation. Maglev trains will save time in transportation. It is possible that this time saving brings different demands. Despite these demands, maglev train km-passenger transport rates reveal that this technology provides per capita environmental contribution [2].

Maglev trains have some advantages over traditional trains. As the train does not touch the ground along the guide road, it does not have any moving parts, so there is no part to wear. For this reason, the maintenance cost is low. Since there is no contact with the guide track, there is no friction. It is less noisy than other trains and as a result of all these advantages, it is high speed [3].

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Reza Nasiri-Zarandi and Arsalan Hekmati have compared different suspension types, traction designs and control techniques applied to maglev trains. He stated that electromagnetic suspension linear asynchronous motors are used in low-speed maglev trains and suggestions are given for both suspension and control systems to increase their performance [4].

Many studies have investigated the effects of aerodynamic distribution. Changda Tan et al. investigated the aerodynamic distribution of maglev trains in the open air and without wind, according to the number of wagons, the highest current flow and the flow structure around the train. It showed that the buoyancy coefficient has a negative correlation as the number of wagons increases [5]. Sha Huang et al also addressed the safety risks of aerodynamic effects. They have listed the necessary precautions to be taken as a result of the pressure that the two trains will apply to each other [6].

Qing Yang et al. Investigated the eddy current effect that emerged as a result of the high-speed operation of the electromagnetic suspension maglev train and investigated the relationship between eddy current and suspension force [7].

Gang Liang et al. Investigated the effect of integration of high-temperature superconductor into the maglev system on system performance. The results showed that the stability of the maglev system depends on the arrangement of high-temperature superconductor stacks for a permanent magnet guideway [8].

You-Lin Xu et al. Analyzed the dynamic response of trains passing through flexible transition viaducts for the Shanghai maglev line and made comparisons with the results of straight and circular viaducts. The results showed that the height difference and the length of the transition viaduct directly affect the lift force and the angular velocity of the vehicle for the vehicles moving along the passageway [9].

Long Zhang and JingYu Huang, in their study, presented a practical guideline by performing a simulation based on in-situ vibration testing and model updating method in maglev system design. The effects of random surface irregularity and distributed magnetic forces are investigated here and the frequency response of the guideway has been analyzed in detail. The results showed that the proposed model can provide a practical response prediction and analysis [10].

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Yongpan Hu et al. created a mathematical model of the eddy current effect that occurs during the high-speed maglev train running at different speeds and investigated its effect on the optimal design of the guideway [11].

Jun-ge Zhang et al. Emphasized the importance of determining the absolute position of the train in maglev train systems in terms of system reliability. They pointed out the necessity of the system by showing that the sensors used for positioning play an important role in condition monitoring, diagnosis and maintenance decisions in general design [12].

Hamid Yaghoubi and his colleagues made a comparison of high-speed trains and maglev trains. Within the scope of this study, some advantages of maglev trains can be listed as follows. Maglev trains compare to high-speed trains with noise, environmental problems, land occupations, loading, speed, acceleration and deceleration, braking, maintenance costs, passenger comfort, safety, travel time, etc. It is superior for reasons such as. Besides, maglev trains can travel at higher angles, so shortening the route and construction of maglev trains in mountainous areas is more preferable to high-speed trains [13].

Wei Xu and Cuiying Huang highlighted the importance of reliability, availability, sustainability and safety management (RAMS) in the development of the maglev train industry. The basic reliability of the system should be ensured according to international standards [14].

Compared with other rail systems in the world, the maglev train example is not available in large numbers. The Northeast superconducting maglev train in America can speed up to 374 miles per hour. The train, which can be used with up to 16 wagons, operates between Washington DC and New York. The lack of electrical resistance in superconducting magnets allows SCMAGLEV to consume 30% less energy than other high-speed maglev trains and 50% less than a commercial aircraft. Reducing the number of vehicles on the roads means big reductions in harmful air emissions. Thanks to this line, 2,000,000 tons of greenhouse gas emissions were achieved [15].

The maglev train, which started operation in 2001 in Shanghai, China, is about 30 km long and can speed 430 km per hour. The train runs between Beijing and Shanghai [16].

Located in Japan, Chuo Shinkansen superconducting maglev train travels between Tokyo and Osaka City at a speed of 505 km per hour [17].

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The maglev train used on the 6.1 km long line in North Korea is designed to speed up to 110 km per hour. It operates between Incheon International Airport and Yongyu Station [18].

The 432km California Nevada Interstate Maglev Project, which will connect California and Las Vegas, has been planned for many years [19].

In Table 1, high-speed trains and maglev train technologies are compared with each other in terms of travel time factors, intermodal compatibility, cost and additional factors [20].

Table 1. Comparison of Maglev Trains and High-Speed Trains [20].

SYSTEM FEATURES	MAGLEV	HSR
a. Travel time factors		
*Maximum speeds	420-450km/h	300-350km/h
*Acceleration rates	Higher at upper speed range	
b. Intermodal compatibility		
*Network connectivity	None/single lines	Excellent/extensive networks
*Use of existing infrastructure	New and elevated guideways, tunnels and station needed	New lines combined with existing lines and stations can be used
c. Costs		
*Investment costs	$12-55M/km	$6*25M/km
*Operating and maintenance costs	Uncertain	Known
*Energy consumption	Higher than HSR	
d. Additional factors		
*Riding comfort		Superior
*System image/passenger attraction	Excellent, plus initial innovation interest	Excellent/ superior network accessibility
*Impacts on surroundings	Lower noise and vibration	Tracks mostly at grade

Maglev trains have been investigated from many aspects in the literature. Suspension types, engine differences, rail design, effects arising from differences in the number of wagons, aerodynamic effects, safety and control requirements can be given as examples to these studies.

In this study, the application for a maglev train line Ankara-Sivas in Turkey, 405 km in length that can be applied economic analysis was conducted for four different versions.

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2. Project Details

The necessary infrastructure must be established for the use of Maglev technology. Maglev trains are not compatible with traditional rail lines. This situation shows that they cannot use the existing infrastructure together. Maglev systems should be designed as a complete transportation system. Within the scope of this study, electromagnetic suspension, linear synchronous motor vehicles will be used in the designed system, and a double-sided guideway has been preferred.

2.1 Levitation Technique

Maglev trains can be classified as electromagnetic suspension (EMS) and electrodynamic suspension (EDS) trains according to suspension systems. In EMS trains, energy is supplied to create an electromagnetic field between the electromagnet placed under the rail and the rail. Thus, the train is suspended. The suspension distance between the electromagnet and the rail takes a value between 8-10 mm. The most important advantage of the suspended maglev system is that it can operate at all speeds. However, this methodology is unstable due to the characteristics of the magnetic circuit. The higher the speed, the harder it is to maintain the air gap. A control system is required for this [21-22]. Fig 1 EMS train for suspension system is observed[21].

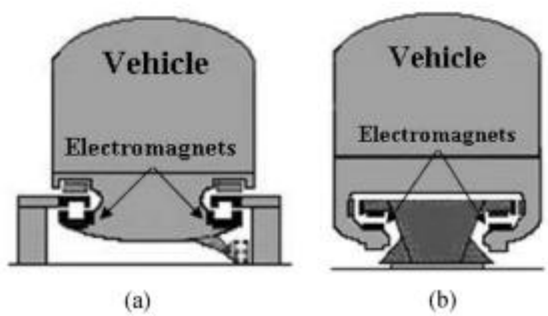

Figure 1. Electromagnetic suspension. (a) Levitation and guidance integrated. (b) Levitation and guidance separated [21].

In obtaining the state equation of the electromagnetic suspension system, magnetic leakage should be neglected. It should be assumed that the electromagnetic gravitational force is at the center of mass and vertical movement should be taken into account.

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State equation of electromagnetic suspension system [23]:

The electrical equation of the electromagnet:

$$u(t) = Ri(t) + \frac{\mu_0 N^2 A}{2} * \frac{\dot{i(t)}}{z(t)} - \frac{\mu_0 N^2 A i(t)}{2} * \frac{\dot{z(t)}}{[z(t)]^2} \quad (1)$$

The electromagnetic force:

$$F(i,z) = \frac{\mu_0 N^2 A}{4} * [\frac{i(t)}{z(t)}]^2 \quad (2)$$

The kinetic force equation of the electromagnetic suspension system is presented:

$$m\ddot{z}(t) = (m+M)g - F(i,z) \quad (3)$$

The mathematical model of the electromagnetic suspension system is obtained so that the state variable is specified:

$$x = (x_1 \;\; x_2 \;\; x_3)^T = (z \;\; \dot{z} \;\; i)^T \quad (4)$$

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \frac{M+m}{m} * g - \frac{K}{m} * \frac{x_3^2}{x_1^2} \\ \dot{x}_3 &= \frac{x_2 * x_3}{x_1} - \frac{R * x_1 * x_3}{2K} + \frac{x_1}{2K} * u \end{aligned} \quad (5)$$

Some expressions in these equations: m: quality of electromagnet, M: equivalent quality of the vehicle, z: suspension gap, i: suspension current, u: suspension voltage, R: resistance, L: length of the electromagnet

2.2 Propulsion

Maglev trains get their driving force from a linear motor. The structure of the linear motor is simpler and more robust than the structure of the conventional rotary motor. Even if the working principle is the same as the rotary motor, the linear motor is superior to the rotary motor since there is no mechanical contact. Linear synchronous motors (LSM) have a magnetic source within

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themselves. The repulsion force is created by this magnetic force. LSMs have a high-efficiency rate in high-speed maglev trains [23].

2.3 Guidance

The rail system in maglev trains is a non-contact system. Magnetic repulsion or magnetic pull force is used in the state of motion as in the suspended state. In the use of the magnetic repulsion force, the lifting coils are connected in opposing two rails and these coils form a guide system. When the train moves, the electromagnets on the train provide a two-sided average so that the train is guided. In magnetic attraction force, the inductance will increase when the train moves. Due to the energy flow direction, the vehicle will be centered and the movement will be provided by the pulling force [10]. Fig 2 shows the costs of one-way and two-way lines for some locations [24].

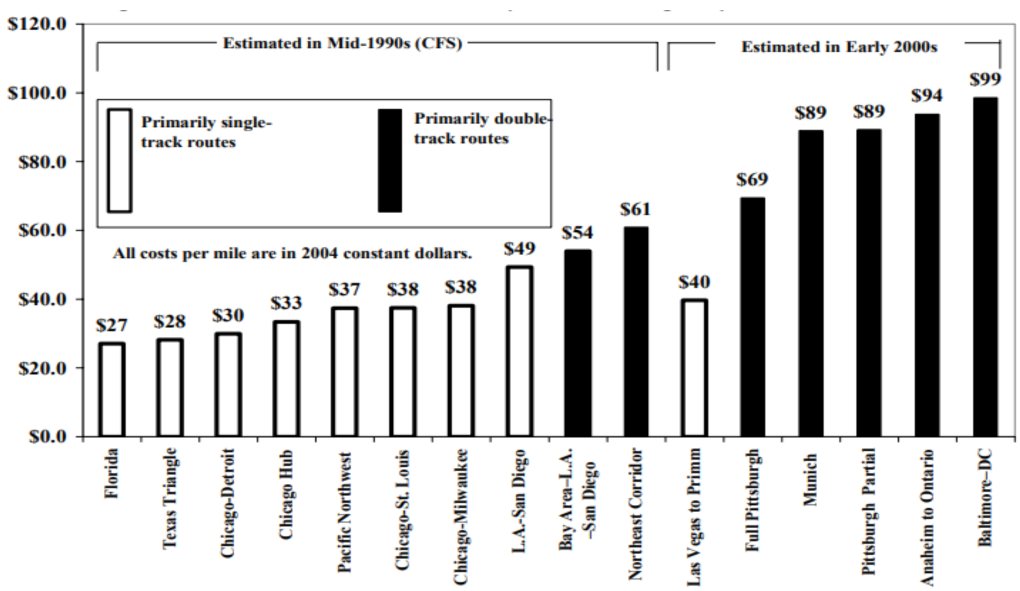

Figure 2. Single and bi-directional guideway cost examples [24].

3. Metodology

In this study, an economic analysis of a maglev line that can be established between Ankara and Sivas has been made for different scenarios. Fig 3 is given in the route of the planned high-speed train line are made in Turkey. This route is 405 km [25]. This route will be used within the scope of the study. There are 49 tunnels with 66.0 8 km and 49 viaducts with 27.2 km along the route [26].

When designing the Maglev line, not only the train but also the necessary infrastructure must be created. A new guiding line should be determined. Rail costs are similar in most of the studies. The cost of the double-track is different from the one-way track but not twice as much. The cost of creating the rails is quite high in the cost of the system. The cost of a duplex track is approximately €17million per km. Besides, one of the most important costs is the vehicle cost. The price of a single wagon is approximately €20 million. Besides these two important costs, station costs are important. Station costs are approximately €40 million for each station [27-28]. Guide rails are designed to be used for 80 years. This time can be accepted as the operation time of the system [27]. In the light of the information contained in Reference 29, it was calculated that the cost of the tunnel is approximately 2.6 times the rail cost on the open road. In this case, the tunnel rail cost is €44million per km [29]. The viaduct cost calculation was calculated using the data in source number 30 and is approximately €21million per km [30]. Electrification and communication control cost is approximately €1.5million per km [31].

Figure 3. Ankara- Sivas HSR Line [25].

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The initial investment costs of the systems for 4 different scenarios are shown below.

3.1. Version 1

If a system is designed for 20 wagons on the approximately 405 km Ankara-Kırıkkale-Yozgat-Sivas line, which consists of 4 stations, the initial investment cost is as in Table 2 below.

The system cost per kilometer is € 24.55 million.

Table 2. Version 1 Investment Costs

	Unit price (million €)	**Quantity**	**Total (million €)**
Rail cost per km (open area)	17	312	5304
Rail cost per km (tunnel)	44	66	2904
Rail cost per km (viaduct)	21	27	567
Vehicle cost	20	20	400
Station cost	40	4	160
Electrification ve Communication Controls cost	1,5	405	607,5
Total initial investment costs			9942,5

3.2. Version 2

If a system is designed for 10 wagons on the approximately 405km Ankara-Kırıkkale-Yozgat-Sivas line consisting of 4 stations, the initial investment cost is as in Table 3 below.

The system cost per kilometer is € 24.05 million.

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Table 3. Version 2 Investment Costs

	Unit price (million €)	Quantity	Total (million €)
Rail cost per km (open area)	17	312	5304
Rail cost per km (tunnel)	44	66	2904
Rail cost per km (viaduct)	21	27	567
Vehicle cost	20	10	200
Station cost	40	4	160
Electrification ve Communication Controls cost	1,5	405	607,5
Total initial investment costs			9742,5

3.3.Version 3

If a system is designed for 20 wagons on the approximately 405km Ankara-Yozgat-Sivas line consisting of 3 stations, the initial investment cost is as in Table 4 below.

The system cost per kilometer is € 24.45 million.

Table 4. Version 3 Investment Costs

	Unit price (million €)	Quantity	Total (million €)
Rail cost per km (open area)	17	312	5304
Rail cost per km (tunnel)	44	66	2904
Rail cost per km (viaduct)	21	27	567
Vehicle cost	20	20	400
Station cost	40	3	120
Electrification ve Communication Controls cost	1,5	405	607,5
Total initial investment costs			9902,5

3.4. Version 4

If a system is designed for 10 wagons on the approximately 405km Ankara-Kırıkkale-Yozgat-Sivas line consisting of 3 stations, the initial investment cost is as in Table 5 below.

The system cost per kilometer is € 23.95 million.

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Table 5. Version 4 Investment Costs

	Unit price (million €)	Quantity	Total (million €)
Rail cost per km (open area)	17	312	5304
Rail cost per km (tunnel)	44	66	2904
Rail cost per km (viaduct)	21	27	567
Vehicle cost	20	10	200
Station cost	40	3	120
Electrification ve Communication Controls cost	1,5	405	607,5
Total initial investment costs			9702,5

After the initial investment cost is calculated, the recycling cost should be calculated. In order to make this calculation, it is necessary to calculate the operating life of the system, annual operating cost, annual passenger capacity along the route, annual income values based on ticket prices.

According to TCDD 2019 sector report, the number of HSR passengers is 6677 per km in 2019 data [32]. According to the related report, this average of 2,704,185 passengers is foreseen for the line of 405 km.

Annual operation and maintenance cost is approximately €154,000 per km[31-33]. Annual maintenance and operating costs for 405km are €62.4 million.

4. Result and Discussion

When looking at 4 different scenarios, the number of wagons or the number of stations does not cause major changes in the total cost. The biggest cost for a 405 km line is the rail and tunnel cost. Considering the number of different stations and wagons, an initial investment cost of €9.70-9.94 billion is required for the line.

The operating cost calculated for this line is approximately €62.4million. If the initial investment costs are excluded from the calculation with the estimation of 2,704,185 passengers, the ticket price of €23 will be sufficient to cover the operating costs.

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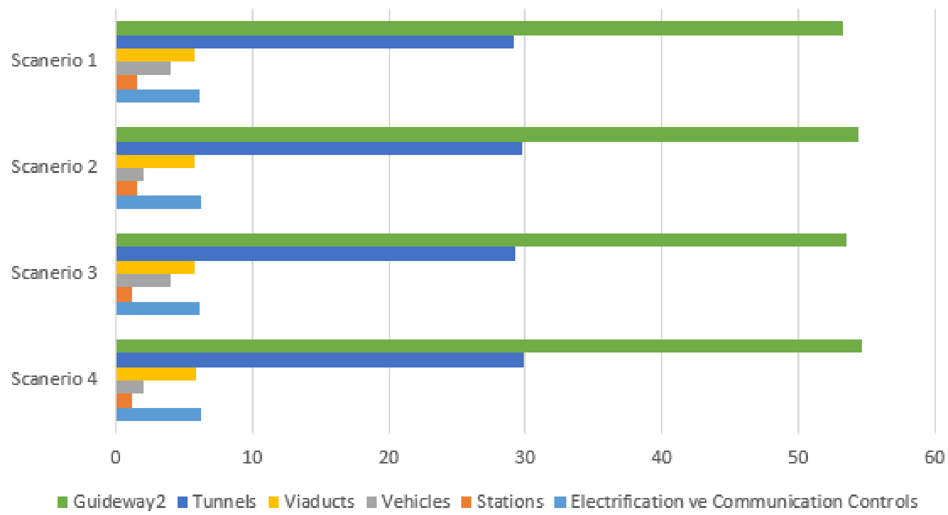

Figure 4. Percentage of parameters in the initial investment cost

5. Conclusion

Maglev train technology is more than other train technologies as an initial investment cost. However, maintenance costs are less than high-speed train technology. The applicability of the route was investigated, taking into account the annual operating and maintenance expenses, the high initial investment cost and the passenger capacity. Population growth estimates and industrial investments on the route should be taken into account. Maglev trains save time due to their high speed. Considering the public interest, it is recommended to increase the applications of maglev train technology due to both economic and environmental benefits.

If it is necessary to make an assessment by keeping the number of wagons at the forefront, according to the cost / benefit analysis, version 1 is 2.1% more costly than version 2 and version number 3 is approximately 2.1% more expensive than version 4, but in version 1, the number of wagons is 2 times the number of wagons in version 2. The number of wagons in version 3 is 2 times the number of wagons in version 4.

If it is necessary to evaluate the number of stations in the forefront, according to the benefit / cost analysis, version number 1 is approximately 0.5% more costly than version number 3 and version number 2 is approximately 0.5% more costly than version number 4, but in version 1, the number

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of stations is 1 more than the number of stations in version 2. The number of stations in version 2 is 1 more than the number of stations in version 4.

Considering all these results, it is seen that the number of stations and wagons does not cause major changes in the initial investment cost. Within the scope of the study, we believe that the application of version number 1 will be more ergonomic.

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