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Investigating Optimum Speed in High-Speed Railway: Istanbul-Ankara Corridor

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In this paper, optimum speed on high-speed railways is investigated according to total costs for the Istanbul-Ankara connection. This connection, whose feasibility studies are completed, will serve both passenger and freight traffic. The high-speed railway route, planned between Istanbul and Ankara, is a part of the TER project (The Trans- European North-South Railway). The total cost investigated for this route includes the traffic independent (constant) costs, traffic dependent (variable) costs and the social (environmental) costs. At the end of the study it was cocluded that the optimum speed at which costs are minimised is 200 km/h for passenger trains and 90 km/h for freight trains.

Keywords: High-speed railway, optimum economic speed, total cost

1. Introduction

Currently there are no railway tracks appropriate for high-speeds in Turkey. A new route is planned from Sofia to Istanbul and Ankara, within the framework of an International Railway Network integration in Europe as shown in Fig 1. The feasibility studies of this route have been conducted by Obermeier Project Management Railconsult. The route, which is a very important connection for Turkey, is not at the construction stage yet. The estimated construction cost of the route, which is planned to be 416 km in length, is 6.65 106 USD. The route will decrease the travel time between the two big cities at a great extent. The motorway, which is a part of the TEM Project, also lies on the same corridor.

Highways carry 95% of the freight and passenger demand in our country. The necessary emphasis is not put on the railways, and their share is gradually decreasing. There are some studies concerning high-speed railways. In the study entitled "The Full Cost of High-Speed Railway" conducted by David Lavinsonet al., the full costs corresponding to the HSR connection between Los Angeles and San Francisco are investigated. In the study made by W. Teichgräber and H. G. Biewald[1], capacity calculation for HSR and its comparison with highways are made. In the study made by W. Schwanhäusser[2], the HSR connections in Germany and their capacities are examined. In the PhD study conducted by Z. Öztürk [3], full costs of motorways and HSR in the Ankara-Istanbul corridor and the changes in costs depening on demand are investigated. In the studies made by G. Ellwanger, the difference between the levels of noise in highways and railways is examined. In the study made by K. A. Small and C. Kazimi[4], air pollution costs of motor vehicles are investigated. In the study made for the Union of International Railways, factors such as accidents, air pollution, noise and climate change and their costs are examined. For the railways, studies that focus on speed optimization and investigate the lowest possible cost depending on speed have been conducted. In the studies made by H. Sliwka[5], E. Brettman[6, 7], F. P. Kotschnew[8], and Z. Tuna[9] the optimum economic speed is investigated.

This study includes some distinguishing points that have not been examined previously. An important HSR connection for Turkey is taken as an example, and the optimum economic speed is investigated. Constant costs, variable costs according to traffic and social costs are taken into consideration.

2. The Daily Number of Vehicles to be Used in Costs

Approximate values for high-speed railways were obtained from the second part of a feasibility study prepared by Obermeier Project Management Railconsult [10-12]. According to the feasibility study that was carried out by the Obermeier Project Group, in case of the construction

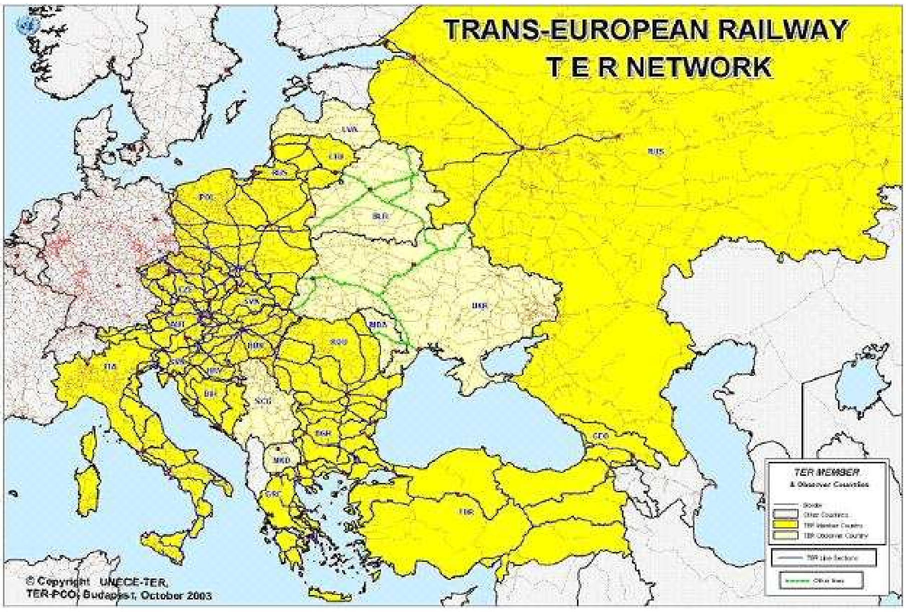

Figure 1. TER network and the high-speed railways of Turkey

of a high-speed railway in this corridor, an annual total transport demand starting in year 2000 at a level of 5.3 million passengers and that will rise to 15 million passengers in 2020, will be of concern. These correspond to a value of 7260 passengers/day-direction in year 2000, and also to the total demand value when freight demand is also included. A demand value of 5085 passengers and 4915 nettons in one day and in one direction is considered to be appropriate and taken as a base in the problem.

For the observed HSR corridor, the freight trains make up 30% of the total trains. Therefore, the percentage of the trains carrying freight was accepted to be 30the total. According to these, the freight vehicle ratio is accepted as 30

As for the taken level of demand, the changes in speed do not affect the capacities of this mode and the numbers of vehicles that are calculated do not vary with the speed. The speed was taken as a parameter only for the formulations of the variable costs.

The high-speed railway is examined taking minimum cross-sectional widths i.e. the high-speed railway is considered as having two tracks. Other parameters will be explained in the related sections of this study[1, 2, 10, 13, 14].

In examining a transportation cost problem, it is important to determine the basic parameter, namely the demand value, accurately in order to specify the number of vehicles to meet this demand, the occupancy rates, the average travelling speeds of these vehicles and the parameters of the railway characteristics. For the high-speed railway in the examined section, whose feasibility study was completed, maximum slope was taken as 12.5 (0%), freight train rate was taken as 30%, and a good and two-tracked operating quality was assumed. With these forming the basis, travelling speeds of passenger trains were accepted as 250 km/h, and those of freight trains were taken as 115 km/h. The average occupancy value for the passenger train was taken to be 210 passengers/train while that of the freight train was taken as 470 net tons/train, [15].

Using these data, the daily number of vehicles for the high-speed railway at the demand value was determined, shown in Table 1. In this table, the necessary number of vehicles in this corridor and the corresponding passenger and freight traffic values for the different freight train rates can be seen. In this study, since only 30% of the freight train rate was taken into account, traffic dependent costs for different speeds were examined.

For the high-speed railway, passenger train

Table 1
The daily railway capacity per direction, [16]

			Freight 0	10	Train 20	Ratio(%) 30
Average min following time	z	min/train	1.64	3.24	2.98	2.88
Average time per delayed train	P_m	min/train	4.00	6.10	8.20	10.3
Probability of capturing fol. events at some elevation	W_g		1.00	0.86	0.70	0.60
Total following delay time during 30 days	P_f	min/30days	151	172	196	223
Average buffer time	r	min/train	4.09	4.58	4.66	4.50
Passenger trains /day	N_v	train/day	230	152	138	125
Freight trains/day	N_m	train/day	-	17	35	54
Total num. trains/day	N	train/day	230	169	173	179
Num. of daily passengers	L_v	pas/day 10^3	48.3	31.9	29.0	26.3
Tons of daily freight	L_m	ton/day 10^3	-	8.00	16.5	25.4

speeds were taken as 100-150-200-250 km/h, and freight train speeds were taken as 45-70-90-115 km/h. Details of the method for finding the number of vehicles can be found in, [3, 16].

Daily operating time (T) was accepted to be 22 hours on the route and daily numbers of trains were calculated using Eq. 1.

$$N = \frac{T}{(r+z)}. \tag{1}$$

70% of the daily trains are passenger trains and the remaining 30% are the freight trains; i.e. 125 out of 179 are passenger trains, while there are 54 freight trains. Number of trains determined according to the demand were approximately 1/5 of the real capacity of the route. According to this, the number of passenger trains were 24, while the number of freight trains were 11. By using the average occupancy rates, daily number of passengers was found out to be 5085, while the daily amount of freight was 4915 tons in Table 2.

3. The Costs

The high-speed railway costs are examined in three groups: which are the traffic independent costs (constant costs), the traffic dependent costs (variable costs) and social costs (environmental costs), Table 3.

The traffic independent costs are defined to be independent from the amount of traffic, whereas traffic dependent costs are affected from the amount of traffic and the change in speed.

3.1. Traffic Independent (constant) Costs

3.1.1. The Depreciation and Interest Cost(C_{c1})

By using the kilometric construction cost ($\imath_1$) for the high-speed railway in Turkey, the depreciation and interest cost of the railway and related constructions are calculated annually (A_1). L is the length of Istanbul-Ankara, HSR and the total length of the planned railway line is 416 km. The kilometric construction cost of HSR is assumed to be 6.65 106 USD. The economic life of the railway (n_1) is 50 years, the residual value (V_k) of the investment cost is 10%, and net interest rate (i) is taken as 0.15. By taking the construction costs per km, the related annual interest and the depreciation coefficients, and by using A_1, the depreciation and the interest costs are calculated as in Eq. 2, [3, 11].

$$C_{c1} = \imath_1 \times A_1 = (\imath_1 - V_k)\frac{(1+i)^{n_1} \times i}{(1+i)^{n_1} - 1} + V_k \times i. \tag{2}$$

Table 2
Number of trains for the high-speed railway, [17]

Number of daily passengers L_v	5085 (pas/day)
Weight of daily freights L_m	4915 (ton/day)
Passenger trains/day N_v	24.18 (train/day)
Freight trains/day N_m	10.54 (train/day)
Total number of trains N	35 (train/day)

Table 3
The high-speed railway costs

1. The traffic independent (constant) costs;
-The depreciation and interest costs,
-The maintenance and repair costs of locomotives and wagons which are independent of traffic,
-Storage service costs,
-General costs.
2. Traffic dependent (variable) costs;
a.The maintenance and repair costs of track and related constructions.
b.The vehicle operating costs;
-Depreciation and interest cost of the rolling stock,
-The traffic-dependent portion of the maintenance and repair costs of locomotives and wagons,
-Cost of the personnel necessary for locomotive maintenance,
-Energy cost,
-Personnel costs,
c.Time cost.
3. The social (environmental) costs;
-Accident costs,
-Air pollution cost,
-Noise pollution cost,
-Cost of the changing climate.

3.1.2. The Maintenance and Repair Costs of Locomotives and Wagons Which are Independent of Traffic (C_{c2})

Because the data about these related costs cannot be obtained, this part is considered in the traffic dependent part of the maintenance and repair costs of locomotives and wagons.

3.1.3. Storage Service Costs (C_{c3})

A traffic ratio (α) is calculated by dividing the railway traffic of the corridor to the total traffic on Turkish State Railways. By multiplying this ratio by the total updated storage costs taken from Transport Costs Book (c_{c3}), the storage costs for this railway corridor are determined as in Eq. 3, [3, 18].

$$C_{c3} = c_{c3} \times \alpha. \tag{3}$$

3.1.4. General Costs (C_{c4})

General costs of the railway corridor are determined by using the same method which was used in the calculations of the storage service costs [18].

$$C_{c4} = c_{c4} \times \alpha. \tag{4}$$

The total constant costs (traffic independent costs) were given in Table 4. The speeds do not have any influence on the constant costs.

3.2. Traffic Dependent (variable) Costs

3.2.1. The Maintenance and Repair Costs of Track and Related Constructions (C_{v1})

The portion of the maintenance - repair cost of the roads and related constructions on railways varies in proportion with the traffic. At the first stage, the value of this cost corresponding to a unit traffic, which is measured per gross ton-km*, should be determined (c_{v1}). The effects of a passenger or freight on maintenance and repair cost are different, therefore D_1 and D_2 demand values are used in gross ton-km[1] units in the formula. This value is multiplied by the term ($d + e \times V$) that is used in finding the effect of track on the maintenance cost. Here, V is the average speed determined per passenger and freight train rate and speeds, which is taken as 167 km/h. Values in Eq. 5, average speed and the related coefficient is valid for this corridor.

By expressing the daily passenger demand in this corridor by D_1, freight demand by D_2 and alignment length by L, the effect of the track on maintenance-repair cost is determined as in Eq.

[1]Gross ton-km: the unit of the measure of work which corresponds to the movement over a distance of one kilometer, of one ton of train, excluding the weight of tractive unit.

Table 4
The constant costs for the HSR (10^6 US$/year)

The depreciation and interest cost	452.73
Storage service costs	1.05
General costs	11.05
(1) Total constant costs	**464.83**

(5)[2]. The passenger and freight demands, D_1 and D_2, in Eq. (5) are taken from the last two rows of Table 2 [3]. According to this, a number of (5085) passengers and (4915) net tons of freight will be carried in direction/day.

The effects of a passenger or freight on maintenance and repair cost are different, therefore ($\eta_1 D_1$) and ($\eta_2 D_2$) demand values are used in gross ton-km units in the formula. The weight to be carried is calculated by multiplying these values by the coefficients $\eta_1 = 1.1$ and $\eta_2 = 1.5$, respectively. In other words, it is required to carry 1.1 tons of gross-weight for carrying 1 passenger and 1.5 tons of gross-weight for carrying 1 net ton. C_{v1} is taken from "Transport Costs Book of State Railways of Turkish Republic". Eq. 5 is given in the PhD study made by Z. Öztürk [3].

$$C_{v1} = c_{v1}(d + e \times V)(\eta_1 D_1 + \eta_2 D_2)L365. \tag{5}$$

3.2.2. The Vehicle Operating Costs

The Depreciation and the Interest Costs of the Rolling- Stock (C_{v2}). Rolling stock park for the high-speed railway in the Istanbul-Ankara corridor is found by taking the sum of the necessary vehicle park at off-peak hours and the additional vehicle park. First, the required vehicle park related value of traffic was calculated. Secondly the vehicle parks for peak hours and probable operational applications were determined. The sum of these three components give the rolling-stock vehicles. The method used in calculating the car park can be summarised as follows; car parks needed for passenger and freight trains are determined separately for every speed interval.

The vehicle-park is taken as, one train for peak hours and two trains when various operational needs are added to these passenger train amounts determined. An important increase in speed decreases the amount of vehicle need on vehicle-park. For example, while approximately 100 km/hour speed train operations require a 15 railway trains, 250 km/hour speed train operations require 8 trains. In the week of research, 1 passenger train contains 11 wagons, and 1 freight train contains 20 wagons. While 45 km/hour speed operations of freight train require 6 trains, 115 km/h speed operations require 4 trains. By using the numbers of passenger wagons, freight wagons and locomotives, the vehicle park was determined.

The depreciation and interest costs of the rolling stock are calculated using Eq. 2 after determining the number of locomotives (n_L), purchase value of locomotive (I_L), residual value of locomotive (R_1), economical life of locomotive (n_2), number of passenger or freight cars (n_W), purchase value of cars (I_C), residual value of cars (R_2), economical life of cars (n_3), and average net interest rate (i). In Eq. 6, the residual value is 10%, the average net interest rate is 0.15, the economic life of a locomotive is 25 years and the economic life of the wagons is 30 years. In the calculation of the depreciation and interest values of locomotives and wagons, distance related cost equations are used. The data are taken from GmbH Pr. Man. and Transport Costs Book of State Railways of Turkish Republic[11, 18].

$$\begin{aligned} C_{v2} &= \sum n_L (I_L - R_1) \frac{(1+i)^{n_2} \times i}{(1+i)^{n_2} - 1} + R_1 \times i \\ &+ \sum n_W (I_C - R_2) \frac{(1+i)^{n_3} \times i}{(1+i)^{n_3} - 1} \\ &+ R_2 \times i. \end{aligned} \tag{6}$$

In this article, Eq. 6 was used because of the lack of data for the application of the other equation. In Eq. 6, depreciation and interest counting is a widely used. The purchase value of locomotive or cars are multiplied by the classic depreciation coefficient found by abstraction of permanent value from the selling price of bought vehicles classic amortization coefficient which is $[(1+i)^n i/(1+i)^n - 1]$.

The Maintenance and Repair Cost of the Locomotives and Cars (C_{v3}): The necessary corridor maintenance-repair cost (c_{v3}) corresponding to a gross ton-km, is determined, and the necessary cost (C_{v3}) for the stated demand value is obtained from Eq. 7 [3]. c_{v3} is taken from "Transport Costs Book of State Railways of

[2]The coefficients d and e are taken as recommended by International Union of Railways (IUR) and the equation $(d + e \times V) = (-0.0697 + 0.0097x167) = 1.55$, i.e. the speeds that we investigate increase the track maintenance cost by 1.55.

Turkish Republic".

$$C_{v3} = c_{v3}(\eta_1 D_1 + \eta_2 D_2)L365. \tag{7}$$

The maintenance and repair cost of locomotives can be formulated depending on the work and operating time by taking the distance and resisting forces into consideration. Similarly, the maintenance and repair cost of the wagons can be formulated depending on the distance, the load carried and the operating time. In the computations, weight and speed parameters are also used. However, based on the insufficiency of the necessary data for the application of these formulations, the usage of the expression given in the study is obligatory.

The Cost of Personnel Necessary for Locomotive Maintenance (C_{v4}): The average daily wage of a railway worker (c_{v4}), number of workers per day necessary for locomotive maintenance and repair (L_W), ratio of the number of days that a worker does not work but gets paid to the number of days he works (x), yearly working hours of the electrical locomotive (L_h), the weights of passenger and freight trains (G), and their speeds (V) are put into Eq. 8 and the costs of personnel necessary for locomotive maintenance are calculated. This equation is accepted and used for railways in Germany and Turkey. Eq. 8 is given in the [19] and it is improved in the PhD study made by Z. Öztürk [3].

The necessary number of daily workers for maintenance of locomotives is 2.1, the ratio of the days the workmen do not work to the days they work is assumed to be 48%, the annual work hours of an electrical locomotive is taken as 5000 hours/year.

$$C_{v4} = \left[\frac{\frac{c_{v4}}{1-x}.L_w.\frac{365}{L_h}}{VG}\right](\eta_1 D_1 + \eta_2 D_2)L365. \tag{8}$$

As a starting point, the daily personnel costs per gross ton-km is determined. Then this value is multiplied by 365, the length of routes, daily gross passenger, and freight demand tonnage. The result is the annual cost of the route. Speed and weight are needed while determining the daily personnel cost per ton-km in the equation.

Energy Cost (C_{v5}): Energy cost per 1 kg-km (c_{v5}), and unit train resistance (w_o) are determined, and from Eq. 9, the yearly energy cost (C_{v5}) of the high-speed railway is found. In Eq. 9, unit train resistance of passenger trains is $w_o = 1.5 + (V^2/4500)$ kg/ton, and for freight trains $w_o = 1.5 + (V^2/2000)$ kg/ton. c_{v5} is taken from "Transport Costs Book of State Railways of Turkish Republic".

$$C_{v5} = c_{v5} w_o(\eta_1 D_1 + \eta_2 D_2)L. \tag{9}$$

Vehicle Personnel Cost (C_{v6}): According to the Routing Instructions of TCDD (The State Railway of Republic of Turkey), there must be 1 (one) train driver, 1 (one) assistant driver, 1 (one) train-chief, and 1 (one) brakeman present on a train. The number of personnel on a train (T_p), the average annual cost per personnel (P_C), annual work hours of one personnel (P_h), the ratio of the number of non-working days that a worker gets paid for to the number of days he works (x) are determined and from Eq. 10, the railway personnel cost (C_{v6}) is calculated [17]. Generally, while operational costs are being determined, vehicle driver and accompanying personnel are taken as separate components of maintenance personnel costs. For this reason, vehicle personnel costs are determined separately.

This equation is accepted and used for railways in Germany and Turkey. Eq. 10 is given in the [19] and it is improved in the PhD study made by Z. Öztürk[3]. The data are taken from "Transport Costs Book of State Railways of Turkish Republic".

$$C_{v6} = \left[\frac{\frac{T_p \times P_C}{P_h(1-x)}}{VG}\right](\eta_1 D_1 + \eta_2 D_2)L365. \tag{10}$$

3.2.3. Time Cost (C_{v7})

In order to determine the value of time spent inside the vehicles for passengers and freight on this transportation system, total travel times (t_1, t_2) for the passengers and the freight are found by using the average travel speed of the vehicles and the stopping times. Moreover, hourly time costs for passengers and freight (c'_t, c''_t) are determined; and the annual time costs (C_{v7}) of this system in this corridor are calculated from Eq. 11, [3, 12]. According to the assumed values of speed, the passenger and freight trains can pass the specified route in 2.5 and 4.2 hours respectively.

The detailed value of time for freight traffic cannot be calculated because of lack of data. In this study time cost is approximately determined [3, 12].

$$C_{v7} = [t_1 D_1 c'_t + t_2 D_2 c''_t]\, 365. \quad (11)$$

3.3. Social (Environmental) Cost (C_{v8})

Transportation systems are the main sources of many negative effects on the environment and living creatures. The most important ones of these effects are taken into consideration here. These costs are denoted in the Eq. 12 as follows: Accident costs for the passenger (C'_a), and for the freight (C''_a), air pollution costs for the passenger (C'_p), and for the freight (C''_p), noise pollution cost for the passenger (C'_n), and for the freight (C''_n), climate cost for the passenger (C'_c), and for the freight (C''_c). By using the necessary unit costs taken from the studies of the Union of European Railways, annual environmental costs (C_{v8}) of the railway in this corridor are determined, [3, 20].

$$C_{v8} = \left[\left(C'_a + C'_p + C'_n + C'_c\right) D_1 + \left(C''_a + C''_p + C''_n + C''_c\right) D_2\right] L365. \quad (12)$$

Since there is no such specific study for Turkey, the average of the results of studies carried out in 17 European countries were used to determine the effects of speed on the environmental costs. Environmental costs are adjusted to the Turkish economical conditions. (GNP per capita in the EU is five times that of Turkey).

The accident cost (C_a): Because there were no studies available in the literature that relate speed with the costs and the number of accidents, cost is taken constant at all speed values. The book of "External Effects of Traffic" published by the Union of International Railways is used as one of the references. This study includes 17 European countries. The method is the same as in calculating the external costs of railway and highway accidents. The external effect of accidents is evaluated as follows in European countries [3, 20],

* Firstly, the subjective value of one individual is determined. To find this value, the cost of taking measures to reduce the accidents is divided by the number of people. This is calculated to be 1008463E for European countries.
    - As a next step, loss in production per death is determined. First, the average life time loss due to the traffic accidents is found, and this is multiplied by average income per capita. From the result of the multiplication, the consumption and insurance expenses of the person if not dead is subtracted to find the net loss in production.
    - Finally, to calculate the external loss of accidents; administrative expenses, medical expenses, compensation expenses and the subjective value of an individual are added to the net loss in production found in the previous step.
* The value of the loss in activity of an individual injured in the accident is determined. This value is 41 893E for European countries.
    - As a second step; from the loss in gross production the loss in consumption and the insurance costs are subtracted to get the net loss in production.
    - The medical and compensation costs, net loss in production and loss in activity are all added together to determine the external cost of each injury. As an average for European countries this value is found to be 43 856E.

Table 5
The external (environmental) costs of railways (E/1000 pas-km E/1000 net ton-km)[20]

The Effects	Passenger (1)	Freight (2)
Accident	1.9	0.9
Air Pollution	2.0	0.7
Noise pollution	3.1	4.7
Climate changing	3.0	1.1

The air pollution cost (C_p): For the observed sector of the railways an electrical traction effort is used, there is almost no air polluting effect of electrical locomotives. Only in the production stage of electricity, some emission can be traced [4].

Since train resistance on the railways becomes seriously important in high speeds, energy costs also increase.

The noise pollution cost (C_n): In the study "The External Effects of Traffic" carried out for

Table 6
The effects of speeds on the external costs on high-speed railways (E/1000 pas-km, net ton-km)[21, 22]

Speeds		100 (45)	150 (70)	200 (90)	250 (115)
Accident	(1)	1.9	1.9	1.9	1.9
	(2)	0.9	0.9	0.9	0.9
Air pollution	(1+2)	1.6	2.5	4.0	6.0
Noise pollution	(1+2)	3.9	4.1	4.3	4.4
Climate changing	(1+2)	2.5	4.0	6.0	9.0

the "Union of International Railways", the constants of the external effects were calculated and are given in Table 5.

For railway vehicles, as their speed increases, they cause more noise. For the observed corridor for different modes, the changes in noise depending on the changes in speed were examined by [3]. Therefore, in this study the results of this previous study were also used. In an advanced study, the change in the noise level on highways and high-speed railways is calculated using the method created by the German Transportation Ministry. Speeds of passenger trains are accepted as 100-150-200-250 km/hour and the speeds of freight train are accepted as 45-70-90-115 km/hour. In this model, length of passenger train is 300 m and all of them are equipped with discbrakes. The length of freight is accepted as 550 meters and it is equipped with slipway frames. Equal traffic demands and freight vehicle ratio (%30) and general noise level are calculated.

For transportation vehicles, curve lines are created in accordance with speed-noise values dB(A) on determined speeds. On high-speed railways, noise variable reflected to noise costs and values are calculated in Table 5 and 6. Noise is greater on freight vehicles than passenger vehicles because the components of vehicles (motor, power transfer parts, types of brakes, vehicle weight, vehicle length etc.) cause more noise. The length of the vehicles and the brake types are important factors in noise.

The Climate Changing Cost (C_c): Some studies were carried out to show the effect of speed on carbon dioxide produced by highway vehicles on seasonal changes. In the study of "Transport Emissions and Planning Policies", some diagrams were presented to indicate the relation between changes in speed and seasonal changes. These diagrams were also taken as a source for this study [21].

Since the train resistance becomes important increasing in the high-speeds, the energy spent and air pollution cost also increase.

For this study, the unit costs calculated for railways formed a base and the effect of speed on external costs was calculated as explained above. The results were given in the Table 6.

Electrical operation in high-speed railways causes almost no air pollution. However, during the production of electrical energy, air pollution may occur. The cost of air pollution is very little in electrical operation.

4. The Variation of Costs Depending on Speed in HSR

In this study, necessary amount of vehicles, passenger counts and amount of freight for every vehicle demanded for one day are determined in Table 2. In order to investigate the effect of passenger and freight transportation on variable costs for different speed values, the equations given at the formulation of costs section were used, taking the corresponding amounts of passengers and freight into consideration; using which, the annual variable costs in Table 7 were obtained.

The variable costs, which vary depending on the traffic and the vehicle and which are the functions of speed, are calculated in the speed ranges stated for the high-speed railway. Since maintenance-repair costs of the locomotives and the railcars for the railway cannot be formulated depending on speed, they are calculated independently from speed [23].

From Table 7, it can be seen that increasing speeds in high-speed railways cause a rapid increment in the repair and maintenance costs of track and related constructions. The reason for this is the growing value of the speed dependent coefficient effect on the track maintenance cost.

Table 7
The costs-speed relationship for the high-speed railway (106 USD /year)

Number	The Costs (1) (2)	Speeds (km/h) 100 (45)	150 (70)	200 (90)	250 (115)
2	2.1.Repair and maintenance costs of track and related constructions	6.83	10.73	14.09	18.25
	2.2.Vehicle Operating costs:				
	a. Depreciation and the interest costs of the rolling stock	19.70	17.09	14.55	12.00
	b. Maintenance and repair costs of locomotives and wagons	4.50	4.50	4.50	4.50
	c. Personnel costs related with the maintenance of locomotives	1.05	0.68	0.52	0.41
	d. Energy cost	1.96	3.26	4.95	7.28
	e. Personnel cost of the train	2.02	1.32	1.01	0.80
3	Total vehicle operating cost (3=a+b+c+d+e)	29.23	26.85	25.53	24.99
4	Time cost	50.48	34.42	27.35	24.59
5	Social (environmental) cost	2.46	3.19	4.24	5.68
6	Total variable cost (6=2+3+4+5)	89.00	75.19	71.21	73.51
7	Total cost = Total constant cost + total variable cost (7=1*+6)	553.83	540.02	536.04	538.34

1*=Table 4

Since the necessary vehicle parks decrease by the increase in speed, the depreciation and the interest cost of locomotives and wagons also decrease. As the maintenance and the repair costs of locomotives and the wagons are formulized independent from speed, they are determined as constant costs. Depending on the increment amount of the speed, the personnel costs related with the maintenance cost of locomotives, the personnel costs of the train and the time cost have a tendency to decrease. Since train resistance on the railways becomes seriously important in high speeds, energy costs also increase. On high-speed railways, when the total variable costs consisting of 5 components versus speed are inspected, it is seen that with a 200 km/h speed of passenger train and a 90 km/h speed of freight train, a decrease until the 3^{rd} speed level, and an increase in more speed levels are observed. The determined results are plotted in diagram in Fig. 2. The values in Fig. 2 are taken from Table 7, and the numbers belonging to the cost components are carried on to the figure. The total variable cost in this system versus speed diagram is plotted as in Fig. 3. The diagram of the total cost is given in Fig. 4.

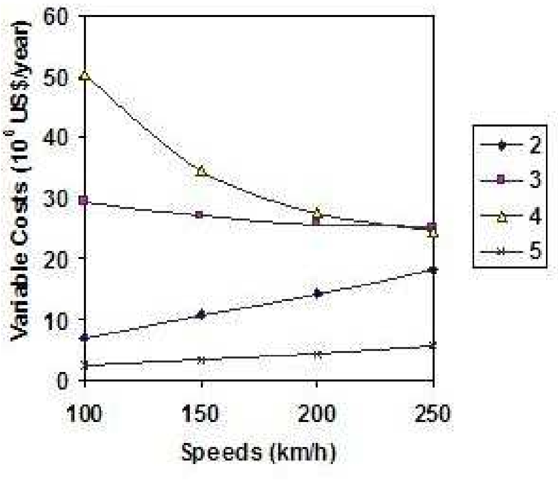

Figure 2. The variation of traffic-dependent costs in relation to speeds in the Sample Corridor for HSR

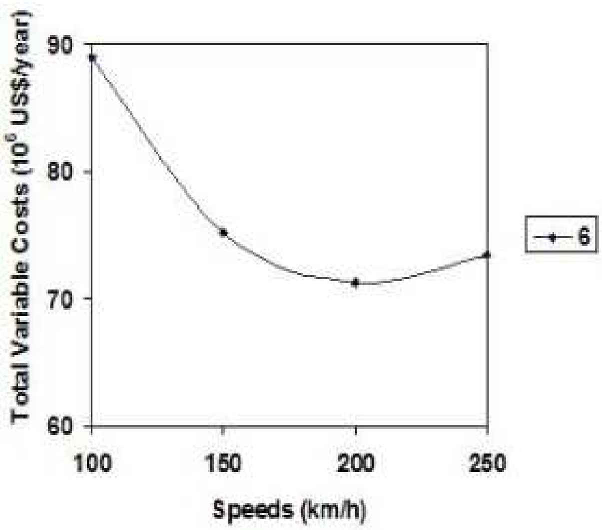

Figure 3. The variation of the total variable costs in relation to speeds for HSR

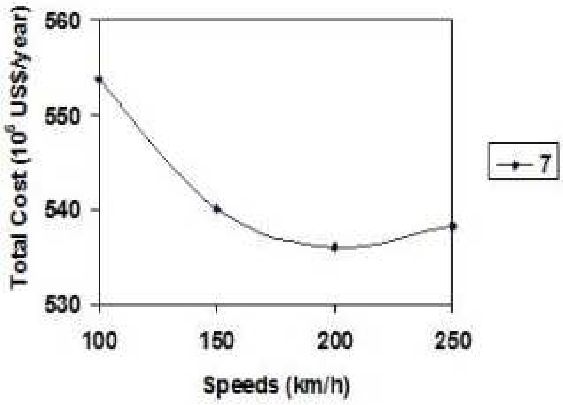

Figure 4. The variation of the total costs in relation to speeds for HSR

5. Conclusions

In this study, optimum speed on the planned HSR connection between Istanbul and Ankara is investigated. This connection, whose feasibility studies are completed, will serve both passenger and freight traffic. This important HSR connection for Turkey is taken as an example and optimum speed is investigated according to total cost. Constant costs, variable costs according to traffic and social costs are taken into consideration. The constant cost for the high-speed railway is 464.8310^6 US$/year. Variable costs for certain speeds are calculated and the speed value, at which total cost is minimised, is determined.

Total variable cost is made up of 4 cost components. These are maintenance and repair costs of railway and related constructions, vehicle operating costs, time cost and social cost. The vehicle operating costs are examined in 5 groups. These are depreciation and interest costs of the rolling-stock, maintenance and repair cost of the locomotives and cars, cost of personnel necessary for locomotive maintenance, energy cost, and vehicle personnel cost. The social (environmental) cost is examined in 4 groups. These are accident cost, air pollution cost, noise pollution cost, and the cost of the changing climate.

In the research, variable costs for different speeds on this route, on which passenger and freight transportation will take place, are calculated. A demand value of 5085 passengers and 4915 nettons in one day and one direction is considered as appropriate and taken as the base in the problem. The following results are obtained;

According to the research made for this demand, it was observed that the total cost is a function of the speed in the high-speed railway.

With the increasing speed, the repair and maintenance costs of the railway and the related constructions and the energy and environmental costs of the high-speed railway increase, while the depreciation and the interest costs of the rolling stock, the personnel costs related to the maintenance of locomotives and the train and the time cost decrease.

The maintenance and repair costs of locomotives and wagons are considered to be constant. The total variable cost and total cost, which is a function of speed and consists of the summation of different costs, decrease up to a 200 km/h-passenger train speed and 90 km/h freight train speed but increase when the speed is more than these values.

As a result, optimum speeds that minimise costs are found to be 200 km/h for passenger trains and 90 km/h for freight trains. Increases are observed at speeds that are higher or lower than these speed values.

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A. Symbols

A_1	Depreciation and interest cost of the railway and related constructions
α	Traffic ratio
c_{c3}	Total storage costs
c_{c4}	Total general costs
c_{v1}	The maintenance and repair cost of roads per gross ton-km
c_{v3}	Maintenance repair cost of the locomotives and cars
c_{v4}	Average daily wage of a railway worker
c_{v5}	Energy cost per kg-km
c'_t	Hourly time costs for passengers
c''_t	Hourly time costs for freight
$C_{i,d}$	Interest and depreciation costs
C'_a	Accident cost for the passenger
C''_a	Accident cost for the freight
C'_p	Air pollution cost for the passenger
C''_p	Air pollution cost for the freight
C'_n	Noise pollution cost for the passenger
C''_n	Noise pollution cost for the freight
C'_c	Climate cost for the passenger
C''_c	Climate cost for the freight
D_1	Daily passenger demand
D_2	Daily freight demand
G	Weights of passenger or freight trains
I_L	Purchase value of locomotives
I_C	Purchase value of cars
$\imath_1$	Kilometric construction cost for HSR
i	Average net interest rate
L_W	Numbers of workers per day necessary for locomotive maintenance and repair
L	Alignment length
L_h	Yearly working hour of the electric locomotive
n_L	Number of locomotives
n_w	Number of passenger or freight cars
n_1	Economic life of the railway
n_2	Economical life of locomotive
n_3	Economical life of wagons
P_C	Average annual cost per personnel
P_h	Annual work hours of one personnel

R_1	Residual value of locomotives
R_2	Residual value of wagons
t_1	Total travelling time for the passengers
t_2	Total travelling time for the freights
T_p	Number of personnel on a train
V	Speed
V_k	Residual value of the investment cost
w_o	Unit train resistance
x	Ratio of the number of days that a worker does not work but get paid, to the number of days he works
η_1	coefficient for passenger
η_2	coefficient for freight