

Energy and exergy efficiencies in Turkish transportation sector, 1988–2004[☆]

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Abstract

This study aims at examining energy and exergy efficiencies in Turkish transportation sector. Unlike the previous studies, historical data is used to investigate the development of efficiencies of 17 years period from 1988 to 2004. The energy consumption values in tons-of-oil equivalent for eight transport modes of four transportation subsectors of the Turkish transportation sector, including hard coal, lignite, oil, and electricity for railways, oil for seaways and airways, and oil and natural gas for highways, are used. The weighted mean energy and exergy efficiencies are calculated for each mode of transport by multiplying weighting factors with efficiency values of that mode. They are then summed up to calculate the weighted mean overall efficiencies for a particular year. Although the energy and exergy efficiencies in Turkish transport sector are slightly improved from 1988 to 2004, the historical pattern is cyclic. The energy efficiency is found to range from 22.16% (2002) to 22.62% (1998 and 2004) with a mean of $22.42 \pm 0.14\%$ and exergy efficiency to range from 22.39% (2002) to 22.85% (1998 and 2004) with a mean of $22.65 \pm 0.15\%$. Overall energy and exergy efficiencies of the transport sector consist mostly of energy and exergy efficiencies of the highways subsector in percentages varying from 81.5% in 2004 to 91.7% in 2002. The rest of them are consisted of other subsectors such as railways, seaways, and airways. The overall efficiency patterns are basically controlled by the fuel consumption in airways in spite of this subsector's consisting only a small fraction of total. The major reasons for this are that airways efficiencies and the rate of change in fuel consumption in airways are greater than those of the others. This study shows that airway transportation should be increased to improve the energy and exergy efficiencies of the Turkish transport sectors. However, it should also be noted that no innovations and other advances in transport technologies are included in the calculations. The future studies including such details will certainly help energy analysts and policy makers more than our study.

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1. Introduction

Several experts have considered that the world's transportation system is not sustainable because the automobile use and density have strongly increased during the last few decades (Steg and Gifford, 2005). As recently stated by Richardson (2005), transportation systems not

only play a major role in the sustainability of the earth but also they, themselves, must be sustained in order to continue to afford to all people access to the economic and social opportunities necessary for meaningful life. Therefore, there are two sides of energy use in transportation. One is about the large contribution made especially by road transportation sources to pollution problems while the other is related to energy supply security for transportation sectors of each country. For this, most of the current studies are concentrated on the area of increasing energy efficiency by better management, operation, energy sources, and transport technologies, etc. (e.g., Liu and Golovitcher, 2003; Burón et al., 2004; Jaccard et al., 2004; Léonardi and Baumgarnyner, 2004; Litman, 2005;

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Shrestha et al., 2005; Simões and Schaeffer, 2005; Steg and Gifford, 2005; Tzeng et al., 2005; Chandrasiri, in press; Ji and Chen, in press; Yedla et al., in press).

Exergy analysis provides a comprehensive framework for energy efficiency. Dinçer (2002) and Marechal et al. (2005) considered exergy as a key instrument for energy and environment policy makers since exergy is a measure of quantity and quality of energy sources unlike energy, which is only about the quantity. One of the most comprehensive definition of exergy analysis was made by Ertesvåg (2005, p. 650) as “quantify the extraction, import, and export of energy carriers, conversion to other energy carriers, and the detailed distribution among different types of users.” Exergy analysis is “a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy and other systems.” (Dinçer, 2002, p. 139).

Although the term “exergy” has been proposed as a “new name for technical availability” by Z. Rant in 1956, the society exergy analyses have started by Reisted (1975) who analyzed the situation of USA in 1970 (Ertesvåg, 2005; Sciubba and Ulgiati, 2005). In spite of some drawbacks of exergy accounting discussed by Valero (2006), the number of experts who use exergy in analysis of energy processes has increased since then. However, although the role of exergy in thermodynamic analyses of technological systems has increased in recent decades, society exergy analyses have been presented for only a few countries (Ertesvåg, 2005). Ayres et al. (2003), who studied exergy, power and work in the US economy between 1900 and 1998, seems to be the first examining the historical exergy data.

The international application of exergy analysis in transportation sector is relatively a new subject. Some of the important studies related with various countries are Schaeffer and Wirtschafter, (1992), Ertesvåg and Mielnik (2000), Ertesvåg (2001), Ayres et al. (2003), Dewulf and van Laugenhove (2003), Federici et al. (2003), Dinçer et al. (2004a,b) and Ertesvåg (2005).

In Turkey, exergy studies started with Ünlü et al. (1987), who examined the Turkish textile industry by using energy and exergy methods. The first study on energy and exergy efficiencies of Turkish transportation sector is by Ünal (1994). Other studies are Rosen and Dinçer (1997), İleri and Güner (1998), Ertesvåg (2001), Hepbaşlı and Utlu (2004), and Utlu and Hepbaşlı (2006). Among them, Hepbaşlı and Utlu (2004) made the only historical investigation from 1990 and 2000 and Utlu and Hepbaşlı (2004) compared only 2 years 1999 and 2000. Other exergy analyses were made for food, textile, and cement (Özdoğan and Arıkoğlu, 1995), for residential-commercial sector (Utlu and Hepbaşlı, 2003,2006), for petroleum production and consumption (Öztürk et al., 2004), for future estimation of the energy and exergy production and consumption (Ceylan et al., 2005), and for optimization of fossil fuel sources (Çamdalı and Ediger, in press).

Turkey is a typical example for emerging energy markets of the developing world. It is a Medium Consumer and has been one of the most successful emerging countries in developing energy consumption capacity for two decades (Ediger, 2003). Its performance is expected to be higher in the future than at present provided that appropriate measures be taken to increase use of energy (Ediger, 2001, 2002, 2004; Ediger and Tatlıdil, 2002). Çamdalı and Ediger, (in press) for instance have shown that a reduction of 1.663 billion US\$ in fossil fuel cost can be made possible by increasing the domestic production of oil and coal and by decreasing imports. Such measures are needed not only for economic development but also human development as shown recently by Ediger and Tatlıdil (in press).

In this study, we aimed at examining energy and exergy utilization in Turkish transportation sector. Unlike the previous studies, historical data is used to investigate the development of energy and exergy from 1988 to 2004. All previous findings are also compared with ours.

2. Materials and methods

In transportation sector, work production processes using electricity and fossil fuel are taken to produce shaft work. The first and second law efficiencies (η and ψ) for this sector can be calculated from Eq. (1)–(2) for electricity and Eq. (3)–(4) for fossil fuels (Utlu and Hepbaşlı, 2004):

$$\eta = \frac{W}{W_e} 100, \quad (1)$$

$$\psi = \frac{E^w}{E^{we}} 100 = \frac{W}{W^e} 100, \quad (2)$$

$$\eta = \frac{W}{m_f H_f} 100 = \frac{m_s \Delta k e_s}{m_f H_f} 100, \quad (3)$$

$$\psi = \frac{E^w}{m_f H_f} 100 = \frac{m_s \Delta k e_s}{m_f \epsilon_f} 100 = \frac{m_s \Delta k e_s}{m_f \gamma_f H_f} 100 = \frac{\eta_f}{\gamma_{ke,f}} 100, \quad (4)$$

where W is the work, W_e the work of electricity, E^w the exergy, E^{we} the exergy of electricity, W^e the exergy of work for electricity, m_f the mass amount of fuels, H_f the enthalpy of fuels, ke the kinetic energy, γ the fuel exergy grade function for hydrocarbon fuels.

As seen in Table 1, data used in this study consist of energy consumption values in tons-of-oil equivalent (toe) for eight transport modes of four transportation subsectors of the Turkish transportation sector given in World Energy Council Turkish National Committee (WEC TNC) (2003, 2004). The subsectors are railways (hard coal, lignite, oil, and electricity), seaways (oil), airways (oil), and highways (oil and natural gas). Energy and exergy efficiency calculations cover the 17 years period from 1988 to 2004

Table 1
Energy consumptions of transportation modes from 1988 to 2004 (in 1000 toe)

Year	Railways				Marine	Airways	Highways		Total
	Hard coal	Lignite	Oil	Electricity	Oil	Oil	Oil	Natural gas	
1988	41	5	161	30	161	397	7332	0	8127
1989	21	5	168	31	175	426	7351	0	8177
1990	10	7	192	30	158	311	8015	0	8723
1991	7	6	200	34	169	352	7537	0	8305
1992	11	1	190	38	198	374	7734	0	8546
1993	11	0	211	41	206	499	9451	0	10419
1994	5	0	219	42	194	556	8888	3	9907
1995	2	0	221	42	226	924	9651	1	11067
1996	7	0	227	46	217	1018	10258	3	11776
1997	5	0	229	52	217	1075	9757	3	11338
1998	5	0	212	56	226	1106	9152	4	10761
1999	4	0	207	57	206	958	9915	4	11351
2000	1	0	207	62	195	1034	10504	4	12007
2001	0	0	171	71	252	1124	10379	4	12001
2002	0	0	178	71	258	363	10530	4	11404
2003	0	0	183	77	280	906	10946	4	12396
2004	0	0	183	83	384	1626	11722	4	14002

because the subsectoral data are available only for this period.

Energy efficiency is calculated following the method described by Rosen and Dinçer (1997). First, weighted mean energy efficiencies are calculated for each mode of transport by multiplying weighting factors (f) with energy efficiencies of that mode (η), where weighting factors are the ratio of energy input of each mode to the total sectoral input. As shown in Table 2, energy efficiencies are the same for each transport mode of four subsectors. The weighted mean overall energy efficiency for a particular year η_t is then calculated by using the following formula:

$$\eta_t = (\eta_{rail}f_{rail}) + (\eta_{sea}f_{sea}) + (\eta_{air}f_{air}) + (\eta_{high}f_{high}). \quad (5)$$

For the year 2000:

$$\begin{aligned} \eta_t &= (\eta_{hc}f_{hc} + \eta_{lig}f_{lig} + \eta_{oil}f_{oil} + \eta_{elec}f_{elec})_{rail} + (\eta_{oil}f_{oil})_{sea} \\ &+ (\eta_{oil}f_{oil})_{air} + (\eta_{oil}f_{oil} \\ &+ \eta_{ng}f_{ng})_{high} = [(28 \times 0.01 + 28 \times 0.00 + 28 \times 1.72 \\ &+ 28 \times 0.52)_{rail} + (15 \times 1.62)_{sea} \\ &+ (28 \times 8.61)_{air} + (22 \times 87.48 + 22 \times 0.03)_{high}]/100 \\ &= 22.54\%. \end{aligned}$$

Exergy efficiency is calculated following Dinçer et al. (2004a,b) and Ji and Chen (in press). The weighted mean exergy efficiencies for each mode of transport are calculated by multiplying weighting factors (f) with exergy efficiencies of that mode (ψ), where exergy efficiencies are the ratio of energy efficiency of each mode to the fuel exergy grade function of the fuels ($\psi\% = (\eta/\gamma)\%$) as given

Table 2
Coefficients of eight modes of transport

Subsectors and modes of transport	Energy efficiency (η %) ^a	Fuel exergy grade functions (γ) ^b	Exergy efficiency ($\psi\% = \eta/\gamma\%$)
Railways (rail)			
Hard Coal (hc)	28	1.04	26.92
Lignite (lig)	28	1.04	26.92
Oil (oil)	28	0.99	28.28
Electricity (elc)	28	1.00	28.00
Seaways (sea)			
Oil (oil)	15	0.99	15.15
Airways (air)			
Oil (oil)	28	0.99	28.28
Highways (high)			
Oil (oil)	22	0.99	22.22
Natural gas (ng)	22	0.92	23.91

^aRosen and Dinçer (1997).

^bSchaeffer and Wirtschafter (1992) and Dinçer et al. (2004a,b).

in Table 2. Weighting factors are the ratio of exergy input of each mode to the total sectoral input. The weighted mean overall exergy efficiency for a particular year ψ_t is then calculated by using the following formula:

$$\begin{aligned} \psi_t &= [(\psi_{hc}f_{hc}) + (\psi_{lig}f_{lig}) + (\psi_{oil}f_{oil}) + (\psi_{elc}f_{elc})]_{rail} \\ &+ [(\psi_{oil}f_{oil})]_{sea} \\ &+ [(\psi_{oil}f_{oil})]_{air} + [(\psi_{oil}f_{oil}) + (\psi_{ng}f_{ng})]_{high}. \quad (6) \end{aligned}$$

For the year 2000:

$$\begin{aligned} \Psi_t = & (\Psi_{hc}f_{hc} + \Psi_{lig}f_{lig} + \Psi_{oil}f_{oil} + \Psi_{elec}f_{elec})_{rail} \\ & + (\Psi_{oil}f_{oil})_{sea} + (\Psi_{oil}f_{oil})_{air} + (\Psi_{oil}f_{oil} \\ & + \Psi_{ng}f_{ng})_{high} = [(28/1.04 \times 0.01 + 28/1.04 \times 0.00 \\ & + 28/0.99 \times 1.72 + 28/1.00 \times 0.52)_{rail} \\ & + (15/0.99 \times 1.62)_{sea} + (28/0.99 \times 8.61)_{air} + (22/0.99 \\ & \times 87.48 + 22/0.92 \times 0.03)_{high}] / 100 \\ = & 22.76\%. \end{aligned}$$

3. Results and discussion

The energy and exergy efficiency values calculated by using Table 2 and formulas (5) and (6) for the years from 1988 to 2004 are given in Tables 3 and 4. Energy efficiency ranges from 22.16% (2002) to 22.62% (1998 and 2004) with a mean of $22.42 \pm 0.14\%$ and exergy efficiency ranges from 22.39% (2002) to 22.85% (1998 and 2004) with a mean of $22.65 \pm 0.15\%$. The reason why exergy efficiency average is slightly higher than energy efficiency average is related to the fact that the Turkish transportation system is

Table 3
Energy efficiencies (%) from 1988 to 2004

Year	Railways					Seaways	Airways	Highways			Overall
	Hard coal	Lignite	Oil	Electricity	Total			Oil	Natural gas	Total	
1988	0.14	0.02	0.55	0.10	0.82	0.30	1.37	19.85	0.00	19.85	22.33
1989	0.07	0.02	0.58	0.11	0.77	0.32	1.46	19.78	0.00	19.78	22.33
1990	0.03	0.02	0.62	0.10	0.77	0.27	1.00	20.21	0.00	20.21	22.25
1991	0.02	0.02	0.67	0.11	0.83	0.31	1.19	19.97	0.00	19.97	22.29
1992	0.04	0.00	0.62	0.12	0.79	0.35	1.23	19.91	0.00	19.91	22.27
1993	0.03	0.00	0.57	0.11	0.71	0.30	1.34	19.96	0.00	19.96	22.30
1994	0.01	0.00	0.62	0.12	0.75	0.29	1.57	19.74	0.01	19.74	22.36
1995	0.01	0.00	0.56	0.11	0.67	0.31	2.34	19.19	0.00	19.19	22.50
1996	0.02	0.00	0.54	0.11	0.67	0.28	2.42	19.16	0.01	19.17	22.53
1997	0.01	0.00	0.57	0.13	0.71	0.29	2.65	18.93	0.01	18.94	22.59
1998	0.01	0.00	0.55	0.15	0.71	0.32	2.88	18.71	0.01	18.72	22.62
1999	0.01	0.00	0.51	0.14	0.66	0.27	2.36	19.22	0.01	19.22	22.52
2000	0.00	0.00	0.48	0.14	0.63	0.24	2.41	19.25	0.01	19.25	22.54
2001	0.00	0.00	0.40	0.17	0.56	0.31	2.62	19.03	0.01	19.03	22.54
2002	0.00	0.00	0.44	0.17	0.61	0.34	0.89	20.31	0.01	20.32	22.16
2003	0.00	0.00	0.41	0.17	0.59	0.34	2.05	19.43	0.01	19.43	22.41
2004	0.00	0.00	0.37	0.17	0.53	0.41	3.25	18.42	0.01	18.42	22.62

Table 4
Exergy efficiencies (%) from 1988 to 2004

Year	Railways					Seaways	Airways	Highways			Overall
	Hard coal	Lignite	Oil	Electricity	Total			Oil	Natural gas	Total	
1988	0.14	0.02	0.56	0.10	0.82	0.30	1.38	20.04	0.00	20.04	22.55
1989	0.07	0.02	0.58	0.11	0.78	0.32	1.47	19.97	0.00	19.97	22.55
1990	0.03	0.02	0.62	0.10	0.77	0.27	1.01	20.42	0.00	20.42	22.47
1991	0.02	0.02	0.68	0.12	0.84	0.31	1.20	20.16	0.00	20.16	22.51
1992	0.04	0.00	0.63	0.13	0.79	0.35	1.24	20.11	0.00	20.11	22.49
1993	0.03	0.00	0.57	0.11	0.71	0.30	1.35	20.16	0.00	20.16	22.52
1994	0.01	0.00	0.63	0.12	0.76	0.30	1.59	19.94	0.01	19.94	22.59
1995	0.01	0.00	0.56	0.11	0.68	0.31	2.36	19.38	0.00	19.38	22.73
1996	0.02	0.00	0.55	0.11	0.67	0.28	2.44	19.36	0.01	19.36	22.76
1997	0.01	0.00	0.57	0.13	0.71	0.29	2.68	19.12	0.01	19.13	22.81
1998	0.01	0.00	0.56	0.15	0.72	0.32	2.91	18.90	0.01	18.91	22.85
1999	0.01	0.00	0.52	0.14	0.67	0.27	2.39	19.41	0.01	19.42	22.75
2000	0.00	0.00	0.49	0.15	0.64	0.25	2.44	19.44	0.01	19.45	22.76
2001	0.00	0.00	0.40	0.17	0.57	0.32	2.65	19.22	0.01	19.23	22.76
2002	0.00	0.00	0.44	0.18	0.62	0.34	0.90	20.52	0.01	20.53	22.39
2003	0.00	0.00	0.42	0.18	0.59	0.34	2.07	19.62	0.01	19.63	22.63
2004	0.00	0.00	0.37	0.17	0.54	0.42	3.28	18.60	0.01	18.61	22.85

Table 5
Comparison with previous studies

Publication	Year analyzed	Energy efficiency (%)	Exergy efficiency (%)
Ünal (1994)	1991	10.00	10.00
Rosen and Dinçer (1997)	1993	22.40	22.40
İleri and Gürer (1998)	1995	15.00	15.00
Ertesvåg (2001)	1995	—	15.00
Utlı and Hepbaşı (2004)	1999	23.88	23.80
	2000	23.71	23.65
Hepbaşı and Utlı (2004)	1990–2000	20.15–23.881	—
		Aver.: 21.70	
Utlı and Hepbaşı, (in press)	2020	28.75	28.85
This study	1988–2004	Range: 22.16%–22.62%	22.39–22.85
		Aver.: 22.42	Aver.: 22.65

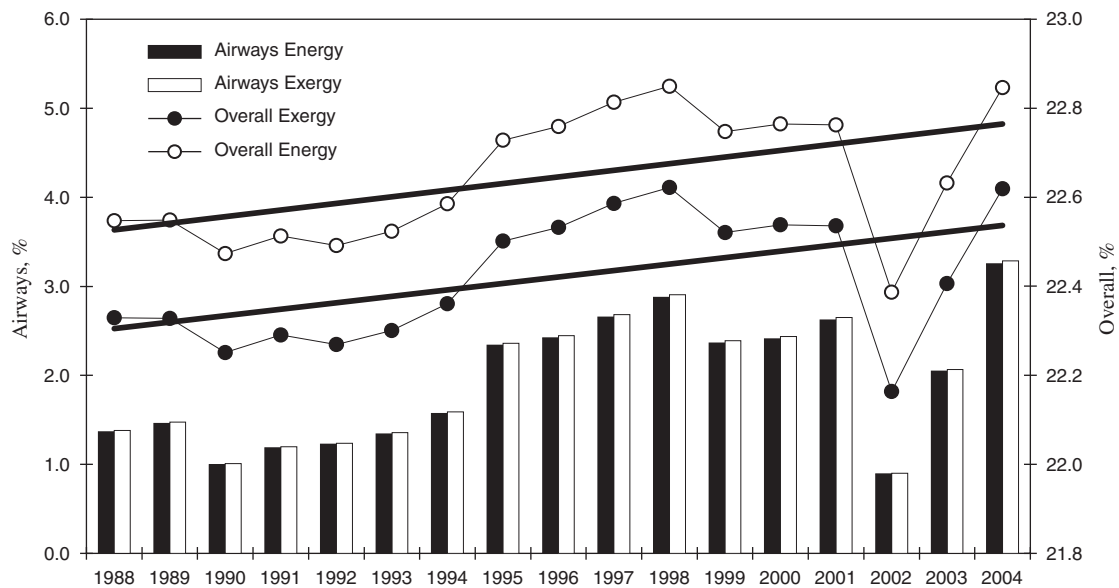


Fig. 1. Overall and airways energy and exergy efficiencies, 1988–2004.

based on oil, which has a relatively lower fuel exergy grade functions than other fuels.

The average (1988–2004) energy and exergy efficiencies of Turkish transport sector calculated in this study is usually smaller than the efficiency values calculated previously (Table 5). The differences are caused by methodology applied in the studies.

Among the previous studies, Ertesvåg (2001) compared the exergy efficiencies of transport sector in Norway (16% in 1985), Sweden (10% in 1980 and 13% in 1994), Italy (10% in 1990), Japan (10% in 1985), Turkey (15% in 1995), Brazil (10% in 1987), Canada (23% in 1986), Finland (10% in 1985), USA (20% in 1970), OECD (15% in 1990), and World (16% in 1990). The best explanation for the differences in efficiencies is with his words: “It is seen that some societies are more ‘efficient’ than others, that is, in the strict thermodynamic sense of the word. However, it cannot be deduced that one society is ‘better’ than another, or more ‘efficient’ in the wider, everyday meaning of the word.” (p. 269).

Time series data of energy and exergy efficiencies correlate almost perfectly with each other with a coefficient

of 0.99 (Fig. 1). They both form two peaks and two troughs in a cyclic pattern between 1988 and 2004. Troughs occur at 1990 (22.25% and 22.47%) and 2002 (22.16% and 22.39%) and peaks at 1998 (22.62% and 22.85%) and 2004 (22.62% and 22.85%), respectively. The linear regression lines fitted to energy ($y = 0.0149x + 22.511$, $R^2 = 0.2635$) and exergy data ($y = 0.0145x + 22.291$, $R^2 = 0.2569$) indicate an improvement in both.

In order to evaluate the factors affecting these patterns, the components of overall energy and exergy efficiencies are examined. Overall energy and exergy efficiencies of the transport sector consist mostly of energy and exergy efficiencies of the highways subsector in percentages varying from 81.5% in 2004 to 91.7% in 2002. The rest of them consisted of other subsectors such as railways, seaways, and airways. The reason for this is that the fuel consumption of highway subsector consist a majority of transportation fuel consumption (Fig. 2). However, the time series of both energy and exergy efficiencies correlate better with those of airways efficiencies than others (Fig. 1). Although only 4.02%–14.38% of overall energy and exergy efficiencies are consisted of airways, the correlation

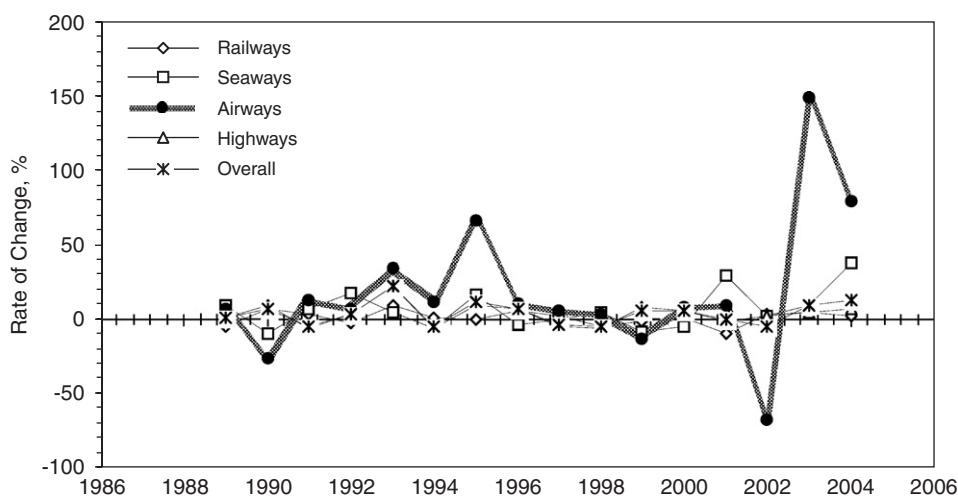


Fig. 2. Variation of rate of change of fuel consumptions in subsectors.

Table 6
Correlation matrices of energy and exergy efficiencies

	Railways	Marine	Airways	Highways	Overall
<i>Energy</i>					
Railways	1.00	-0.34	-0.62	0.57	-0.50
Marine		1.00	0.14	-0.21	-0.02
Airways			1.00	-0.99	0.98
Highways				1.00	-0.97
Total					1.00
<i>Exergy</i>					
Railways	1.00	-0.34	-0.62	0.56	-0.51
Marine		1.00	0.14	-0.21	-0.02
Airways			1.00	-0.99	0.98
Highways				1.00	-0.97
Total					1.00

coefficient between them are 0.98 (Table 6). On the other hand, a perfect inverse correlation exists between highways and airways with a coefficient of -0.99 .

The reason why overall energy and exergy efficiencies are dependent more on airways than others is related to airways' having the highest energy and exergy efficiencies. As shown in Table 2, airways energy and exergy efficiencies are both 0.28. Besides the changes in annual fuel consumptions of airways is bigger than the others (Table 7). The rates of change in airways vary from -67.7% in 2002 to $+149.6\%$ in 2003, whereas the others vary from -10.4% (railways in 2001) to $+37.1\%$ (seaways in 2004).

4. Conclusions and recommendations

As a result of this study, we reached to the following conclusions:

(1) Although the energy and exergy efficiencies in Turkish transport sector are slightly improved from 1988 to 2004, the historical pattern is rather cyclic.

Table 7
Rate of change of fuel consumptions in subsectors

	Minimum (%)	Year	Maximum (%)	Year
Railways	-10.4	2001	+9.6	1993
Seaways	-9.7	1990	+37.1	2004
Airways	-67.7	2002	+149.6	2003
Highways	-6.2	1998	+22.2	1993
Overall	-5.1	1998	+21.9	1993

- (2) The overall efficiency patterns are basically controlled by the fuel consumption in airways in spite of this sector's consisting only a small fraction of total.
- (3) The major reasons for this are that airways energy and exergy efficiency is greater than those of the other subsectors and that the rate of change in fuel consumption in airways are greater than those of the others.
- (4) Since oils are used more than the other fuels in transportation sector, the values of energy and exergy efficiencies are very close.
- (5) This study shows that airway transportation should be increased to improve the energy and exergy efficiencies of the Turkish transport sectors.

However, it should be reminded that using generalized energy and exergy efficiency values for each subsectors has been carried out in this study. No innovations and other advances in transport technologies are included in the calculations. The future studies including such details will certainly help energy analysts and policy makers more than our study.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.enpol.2006.03.021](https://doi.org/10.1016/j.enpol.2006.03.021).

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