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A Study of Energy Efficiency in Rail Vehicles

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Abstract: Today, rail vehicles are frequently preferred both in urban and intercity transportation due to their high passenger capacity, speed and increasing environmental awareness. As in every field, energy efficiency studies have become compulsory in these vehicles. Because, they have high energy consumption even in their daily services. For energy efficiency, there are various strategies such as electrification losses reduction, utilization of regenerative braking and improvement of comfort function and efficient driving techniques have been performed in this paper. For this purpose, firstly, the driving of a rail vehicle has been modeled on Matlab considering all vehicle information, track information and operational constraints. Then, four different driving styles have been determined for the efficient use of energy and their effects on travel time and energy consumption have been examined. The study has been tested with the practical data of Ankaray metro line which has eleven stations and is 8.527 km long. According to the results of the paper, coasting control is more effective for long distances and reduction of the maximum speed is more convenient for short distances. Furthermore, it has been demonstrated that thanks to the determined strategies, the vehicle can save up to 11.54-36.37% energy compared to practical driving.

Keywords: Rail vehicle, modeling, efficient driving techniques, energy consumption, travel time

Raylı Araçlarda Enerji Verimliliği Çalışması

Öz : Günümüzde raylı sistem araçları yüksek yolcu kapasiteleri, hızları ve artan çevre bilinci nedeniyle şehir içi ve şehirlerarası ulaşımda sıklıkla tercih edilmektedir. Her alanda olduğu gibi, raylı sistem araçlarının günlük servislerinde bile yüksek enerji tüketimine sahip olmasından dolayı bu araçlarda da enerji verimliliği çalışmaları zorunlu hale gelmiştir. Raylı sistemlerde enerjinin verimli kullanılmasını sağlamak için çekiş kayıplarının azaltılması, rejeneratif enerjinin kullanılması ve konfor fonksiyonlarının iyileştirilmesi gibi çeşitli stratejiler vardır ve bu çalışmada verimli sürüş teknikleri uygulanmıştır. Bu amaçla, öncelikle, araca ait bilgiler, yola ait veriler ve operasyonel kısıtlamalar göz önünde bulundurularak, bir demiryolu aracının sürüşü Matlab'da modellenmiştir. Daha sonra, enerjinin verimli kullanımı için dört farklı sürüş stili belirlenmiş ve bunların seyahat süresi ve enerji tüketimi üzerindeki etkileri incelenmiştir. Çalışma 11 istasyonlu ve 8.527 km uzunluğundaki Ankaray metro hattının pratik verileriyle test edilmiştir. Çalışmanın sonuçlarına göre, uzun mesafeli istasyonlar için boşta gitme stili, kısa mesafeli istasyonlar için maksimum hızın azaltılması stili daha etkilidir. Ayrıca belirlenen stratejiler sayesinde aracın pratik sürüşe göre % 11.54-36.37 oranında enerji tasarrufu sağlayabildiği gösterilmiştir.

Anahtar Kelimeler: Raylı araç, modelleme, verimli sürüş tekniklikleri, enerji tüketimi, seyahat süresi

1. Introduction

Rapid population growth limited natural resources, industrial and social developments, greenhouse emissions and their consequences in terms of energy is one of the great challenges that society has to face in recent years. Particularly, for the last thirty years, various efforts such as energy efficiency, increasing the use of renewable energy sources and keeping emission at a certain limit have been made to overcome these problems.

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The transport sector, which is directly affected by all these situations and has a high share in energy consumption, directly affects urban life and has been faced various problems. It has been tried to find solutions to the problems in this sector by expanding public transport, improving efficiency standards in vehicles and using environment friendly fuels.

Rail systems stand out in the transport sector because they are reliable, economical and punctual[1] and they can carry more passengers in less time and with less energy than other transport vehicles . There is growing interest in rail systems and the rail network is expanding worldwide. Therefore, until 2023, it is aimed to establish a new 12000 km long high-speed train and freight network in Turkey, to construct a new 30000 km long railway network in EU countries, and to raise total railway network in China to 120.000 km long [2].

Besides these positive developments, even though the rail systems consume less energy than other vehicles, the electricity consumption of these systems is still high [3]. It would not be wrong to say that the rail systems will be the biggest electricity consumer especially in metropolitan cities in the years to come. Therefore, the efficiency studies in rail systems will greatly affect the daily energy consumption and will be beneficial in terms of operational costs. The rail systems consist of different subsystems such as rail network, trains, signaling, electrification and communication. So, the energy consumption of such a complex system varies depending on various parameters [4] and it has been provided to use energy efficient by using different methods in railway systems. The contents of some of these and some examples from the literature are given below [5].

- Increase of power supply level of rail systems

Rail systems are operated electrically. As the level of power supply level is increased, the losses in electrification system is decreased. Therefore, the energy consumption is reduced. Açıkbaş and Söylemez stated that 10% energy saving will be provided when 1500 VDC feed power is used instead of 750 VDC in Üsküdar-Ümraniye metro line [6].

- Utilization of regenerative energy

Since most substations use a non-reversible rectifier, the electrical energy converted from the kinetic energy generated during braking of rail vehicles cannot go back to the grid. Thus, this energy is generally lost and burned in the braking resistors, but it can be reused by various ways. Su et al. designed a numerical algorithm and the help of this algorithm, it was possible to transfer the energy of braking train to another accelerating train in an opposite track [7]. Lu et al. proposed a method using the Bellman-Ford algorithm to increase total regenerative energy and it was increased by 17.23% [8]. Fernandez et al. investigated two real European metro lines; Italian and Spanish metro line. They stated that most of the regenerative energy was wasted in these and 98% of the regenerated energy can be reused for short interval of trains [9].

- Development of Energy Storage Systems

The energy generated during braking can be stored for later use by using various energy storage systems such as battery, volan, flywheel, ultra-capacitor. Barrero et al. proposed the use of different supercapacitors, ranging from 0.91 kwh to 1.56 kwh, for energy savings and these systems provided 24-28% energy savings although they increased the load [10]. Meinert used concept of hybrid energy storage units; the combination of double capacitor- DLC energy storage unit and traction battery and
this concept provided that energy stored up to 2.5 km and saved up to 10.8 % [11].

- Comfort Function

It consists of improved passenger stations, depots, signaling system, ventilation system, groundwater pumps, tunnel lighting. Zhang and Wei tried to determine the role of air condition systems on energy consumption and emission in a metro system with various measurements and data analysis [12]. Ordody investigated the main features of existing ventilation system in Budapest metro and defined a new economic main ventilation system considering technical requirements [13].

- Energy Efficient Driving

Energy efficient driving techniques include many different methods such as different driving practices, optimization of driving regimes, coasting points and time schedule etc. that reduce energy consumption and improve passenger comfort. Su et al. introduced an optimal train control model simulator and investigated different energy efficiency strategies such as reduction of train mass, improvement of kinematic resistance, increase of the maximum traction and braking forces, timetable optimization in order to reduce energy consumption [3]. Martinis and Gallo optimized train speed profiles and an optimization framework was developed considering two cases; with and without energy recovery systems [14]. Yang et al. formulated an integer programming model including speed control and timetable control to evaluate efficiency operations in metro systems and energy consumption decreased by 7.31% with this model [15]. Montrone et al. defined an algorithm with multi-objective and multidisciplinary optimization to find the running times which minimize energy consumption [16]. Liu et al. proposed a numerical method to solve the energy efficiency problem on a line with a steep downhill segment and they managed to reduce energy consumption by 10.90% [17].

The main purpose of this study is to investigate the effects of efficient driving techniques on energy consumption and travel time. The reasons for choosing this method are that it is easy to implement and does not increase cost. In this paper, firstly, driving of a rail vehicle is modeled dynamically in Matlab. It is seen that some parameters are fixed or neglected in the literature because of the complexity of the system and nonlinear change of parameters. Therefore, all parameters and all operational constraints are included in the modelling process as a contribution to literature. Then four different driving cases have been created by using vehicle's driving phases (acceleration, cruise, coasting and braking). The first of these cases is the practical driving of the vehicle in daily life and the others have been designed with efficient driving techniques and pre-targeted travel times in mind. In order to show effectiveness of the study, the practical data of Ankaray metro vehicle which is currently serving in Ankara have been used. According to the results of the study, when practical driving and other driving cases are compared, energy can be saved up to 11.54%, 16.84-

25.096% and 36.37% in the Case 2 (coasting driving style), Case 3 (max. speed reduction driving style with 5% delay and 10% delay) and Case 4 (coasting driving with maximum speed reduction driving style) respectively. Accordingly, the driving styles created by efficient driving techniques provide significant savings in terms of energy consumption.

2. The Problem Definition

2.1. The Motion of the Rail Vehicle

The energy consumption of a rail vehicle, which is responsible for the majority of the total energy consumption consumed by a rail system, can be divided into two main classes. The first class is the energy used for the motion of the vehicle and called as traction energy. The other is the energy used for various comfort functions such as heating and cooling in the vehicle and called as non-traction energy [5]. In this study, energy consumption related to the motion of the vehicle has been tried to be reduced.

The motion of a rail vehicle is mainly examined according to Newton's second law [18-19]:

$$\sum F = m_e \cdot a \tag{1}$$

where F is all the different forces on the rail vehicle (kN), m_e is the equivalent mass (kg) and α is the acceleration (m/sec^2). The equivalent mass can be calculated as follows:

$$m_e = m \cdot (1 + 0.06 + 0.15) \tag{2}$$

where m is the mass of the rail vehicle, the numbers 0.06 and 0.15 refer to the coefficient related to the rotating mass and passenger mass respectively [20]. Equation 1 can be re-arranged as follows due to many forces acting on the rail vehicle during the motion of the rail vehicle:

$$F_m - F_{rr} - F_{rs} - F_{rc} = m_e * a \tag{3}$$

where F_m is the traction or braking force of the rail vehicle depending on the general characteristics of the engine. F_{rr} is the rolling resistance, that is, the sum of the mechanical forces which act to prevent forward movement of a rail [19-21]. This force can be calculated as follows and corresponds to a different value for each speed of the rail vehicle.

$$F_{rr} = a_{rr} + b * v + c * v^2 \tag{4}$$

where v is the speed of the rail vehicle (m/sec), α_{rr}, b and c correspond to coefficients related to the mass, mechanical and air forces respectively [22]. When the rail vehicle is moving up or down, the gradient force (F_{rs}) generated parallel to the track can be calculated as follows (19-20):

$$F_{rs} = m * g * \sin(\phi) \tag{5}$$

where m is the mass of the rail vehicle, g is the acceleration of gravity (m/sec^2), Ø is the angle of the gradient. When the rail vehicle moves along a curve path, the external forces that slow the forward motion of the rail vehicle are called the curve force (F_{rc}) and can be calculated as follows [20-21]:

$$F_{rc} = \frac{d}{p - e} \tag{6}$$

where p is the radius of curve, d and e are considered as follows [19]:

i. d=0.65 m
ii. e=55 m for p greater than 350 m
iii. e=65 m for p between 250 and 350 m.

The energy consumption of a rail vehicle can be calculated by two different ways. The first one depends on the distance and can be calculated as follows [21]:

$$E = \int_{s_1}^{s_2} F_m * ds \qquad (7)$$

where s_1 and s_2 are the starting and finishing position of the rail vehicle respectively. The second one depends on travel time and can be calculated by help of Equation (8) and Equation (9).

$$P_{(i)} = v_{(i)} * F_{m(i)} \qquad (8)$$

$$E = \int_{i=0}^{j} P_{(i)} * dt \qquad (9)$$

where $P_{(i)}$ is the power value at i-step, (kW), t is travel time (sec), E is the energy consumption (kJ).

2.1. Driving Phases

Another condition that affects the energy consumption of the rail vehicle during motion is the driving phases followed by the rail vehicle. These are acceleration (AC), cruise (CR), coasting (C0) and braking (BR) and shown in Figure 1 [18].

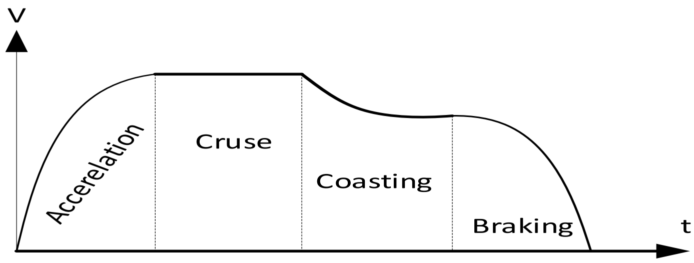


Figure 1. Rail vehicle driving phases

2.1.1. Acceleration

In this phase, the traction force is applied to the rail vehicle and the rail vehicle is accelerated. The corresponding equations (acceleration, speed, distance, energy consumption) are given in below. The continuous time equations in the rail vehicle driving can be discretized in time interval ($t_{step)}$ for j-steps as (18):

$$t_{step} = \frac{t}{j}; i = 0,1,2...j \qquad (10)$$

$$F_m \ \phi \ F_{rr} + F_{rs} + F_{rc} \qquad (11)$$

$$a_{tr(i)} = \frac{F_m - F_{rr} - F_{rs} - F_{rc}}{m_e} \qquad (12)$$

$$v_{(i+1)} = v_{(i)} + \left(a_{tr(i)} * t_{step}\right), v_{(0)} = 0 \qquad (13)$$

$$s_{(i+1)} = s_{(i)} + \left(\frac{\left(v_{(i)} + v_{(i+1)}\right)}{2}\right) * t_{step}, s_{(0)} = 0 \qquad (14)$$

$$E_{(i+1)} = E_i + \left(\left(F_{m(i+1)} * v_{(i+1)}\right) * t_{step}\right), E_{(0)} = 0 \qquad (15)$$

where i is the number of steps, $\alpha_{tr(i)}$, $v_{(i)}$, $s_{(i)}$, $E_{(i)}$ represent traction-acceleration, speed, distance and energy consumption at step (i) respectively. The initial values of the parameters are assumed to be zero.

2.1.2. Cruise

In this phase, the speed of the rail vehicle is constant, and the traction force is equal to sum of the other forces. The basic equations in this phase are given below and the other equations can be derived according to Equation (12-15) [18]:

$$F_m = F_{rr} + F_{rs} + F_{rc} \tag{16}$$

$$v_{(i+1)} = v_{(i)} \tag{17}$$

2.1.3. Coasting

The rail vehicle does not consume energy, i.e. the engine moves by inertia, the mechanical energy is null. Therefore, the speed of the rail vehicle is reduced and the amount of energy consumption retains constant. In this motion phase [18]:

$$F_m = 0; F_m \ \pi \ F_{rr} + F_{rs} + F_{rc} \tag{18}$$

$$E_{(i+1)} = E_{(i)} \tag{19}$$

2.1.4. Braking

The braking force is applied to the rail vehicle. In this driving phase [18]:

$$F_m \ \pi \ 0; F_m \ \pi \ F_{rr} + F_{rs} + F_{rc} \tag{20}$$

The safe braking distance to stop at the station can be calculated as follows [22]:

$$s_b = \frac{v^2}{2 * a_{br}} \tag{21}$$

where s_b is the braking distance, a_{br} is the braking-acceleration.

3. Results and Discussion

3.1. Modeling and Analysis

The driving of a rail vehicle has been modeled in Matlab by using the equations given above. During modeling, all driving phases of the motion of the rail vehicle have been used. The framework of the modeling process is shown in Figure 2.

After the modeling process, energy efficient driving techniques have been used to reduce the energy consumption. For this purpose, four different driving cases have been determined. These driving cases have been called as practical driving style, coasting driving style, maximum speed reduction driving style and combination of maximum speed reduction with coasting driving style respectively. These are described below.

2.1.5. Case 1 (Practical driving)

The first driving style shows the practical driving style currently used on railways. It has been determined after literature studies and interviews with rail system operators and will allow comparison with other driving styles. This driving focuses travel time rather than the energy consumption value. The following steps have been identified in this driving style's modeling.

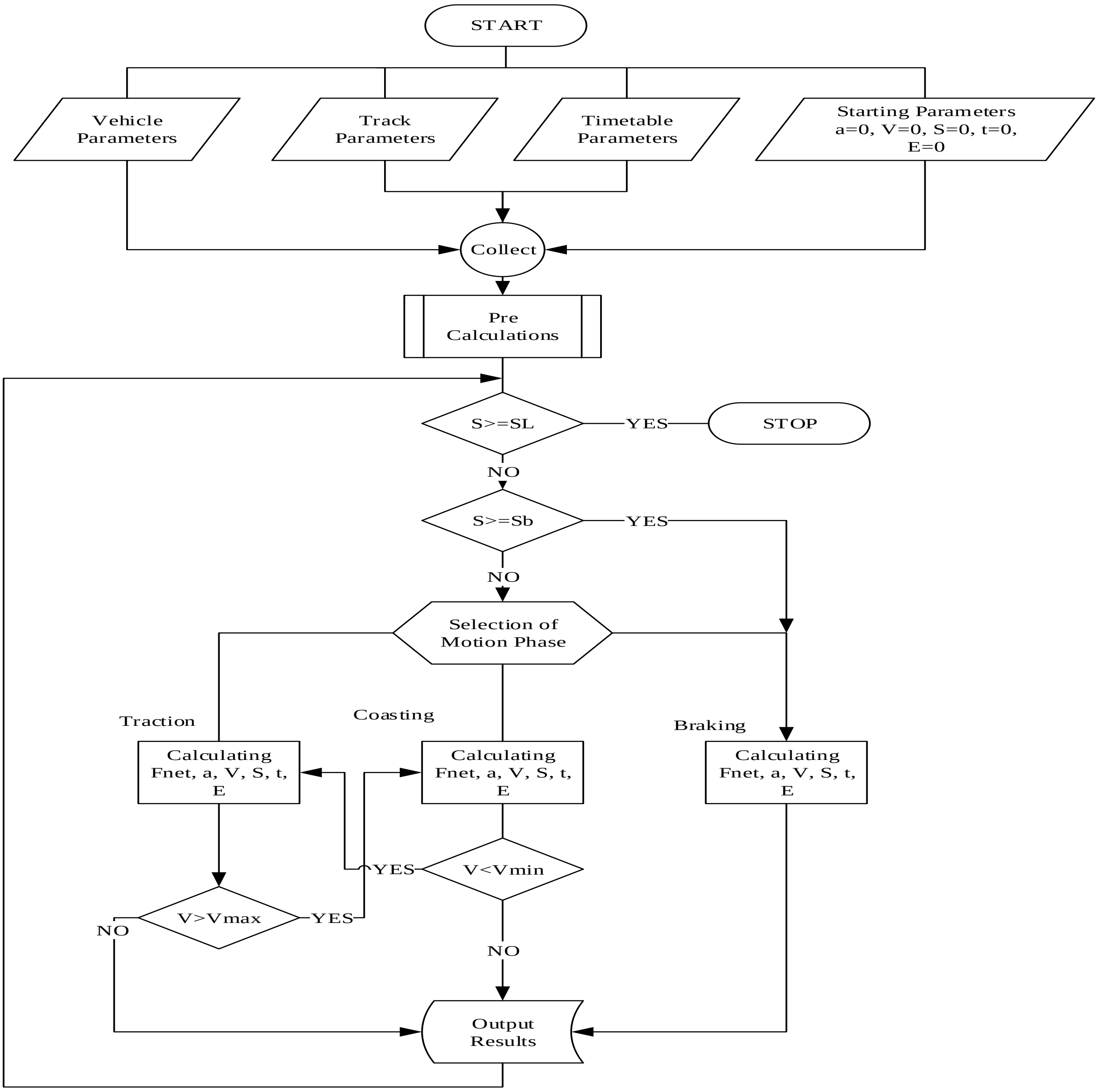


Figure 2. The framework of the modeling

Steps
Step 1: Assigning initial parameters and divide section of distance and time (s_{step}), (t_{step})
Step 2: Acceleration phase to until maximum speed limit and check distance and track parameters.   **(if there is constraints and different parameters, change parameters).**   **When the maximum speed is reached go to Step 3.**
Step 3: Cruise phase and check the braking distance, distance and track parameters (if there is constraints and different parameters, change parameters).   **When the braking distance is reached, go to step 4.**
Step 4: Braking phase

Step 5: Stop at the station
Step 6: Results; Determination t_{min} and E_{max}

2.1.6. Case 2 (Coasting driving)

Since there is no energy consumption in the coasting phase, it will make a positive contribution to the energy savings. The contents of this driving have been described as follows:

Steps
Step 1: Assigning initial parameters and divide section of distance and time (s_{step}), (t_{step})
Step 2: Acceleration to until maximum speed limit and check distance and track parameters. (if there is constraints and different parameters, change parameters). When the maximum speed is reached go to Step 3.
Step 3: Coasting phase and check the coasting minimum speed value, distance, braking distance and track parameters. (if there is constraints and different parameters, change parameters).
Step 4: Return step 2 when coasting minimum speed is reached and braking distance is not reached. When the braking distance is reached, go to Step 5.
Step 5: Braking phase
Step 6: Stop at the station
Step 7: Results; Determination t and E

2.1.7. Case 3 (Maximum speed reduction driving)

In this form of driving, the travel time result of practical driving is utilized and the maximum speed limit has been determined again according to a 5% and 10% delay in travel time. This driving style is suitable for sparse time interval. The contents of this driving have been described as follows:

Steps
Step 1: Assigning initial parameters and divide section of distance and time (s_{step}), (t_{step})
Step 2: Determination of $t=t_{min}+(0.05*t_{min})$ and $t=tmin+(0.1*tmin)$
Step 3: Determination of r, r=r+0.1, and $v_{max}=_{Vinital}+r$
Step 4: Acceleration to until maximum speed limit and check distance and track parameters (if there is constraints and different parameters, change parameters). Check travel time and if it is greater than > t, return to Step 3 When the maximum speed is reached and travel time<t, go to Step 5 When the braking distance is reached and travel time<t, go to Step 6
Step 5: Cruise phase and check the braking distance and travel time. Check travel time and if it is greater than > t, return to Step 3, When the braking distance is reached and travel time<t go to Step 6
Step 6: Braking phase
Step 7: Stop at the station
Step 8: Results; Determination t and E

2.1.8. Case 4 (Coasting and maximum speed reduction driving)

In this style of driving, the 2nd and the 3rd case have been combined. The contents of this driving have been described as follows:

Steps
Step 1: Assigning initial parameters and divide section of distance and time (s_{step}), (t_{step})

Step 2: Determination of t=tmin+(0.05*tmin)
Step 3: Determination of r , r=r+0.1 and $v_{max}=v_{initial}+r$
Step 4: Acceleration to until maximum speed limit and check distance and track parameters **(if there is constraints and different parameters, change parameters).** **Check travel time and if it is greater than > t, return to Step 3** **When the maximum speed is reached and travel time<t, go to Step 5** **When the braking distance is reached and travel time<t go to Step 6**
Step 5: Coasting phase and check the braking distance, coasting minimum speed value **Check travel time and if it is greater than > t, return to Step 3,** **When coasting minimum speed is reached and braking distance is not reached, Return Step 4** **When the braking distance is reached and travel time<t go to Step 6**
Step 6: Braking phase
Step 7: Stop at the station
Step 8: Results; Determination t and E

2.2. A Case Study

This section describes the part where the study has been tested and implemented using real rail system data. For this purpose, the vehicle parameters, track parameters, operational parameters of Ankaray metro line which is currently operating between Aşti and Dikimevi, have been used and the rail network of Ankaray is shown in Figure 3 [23].

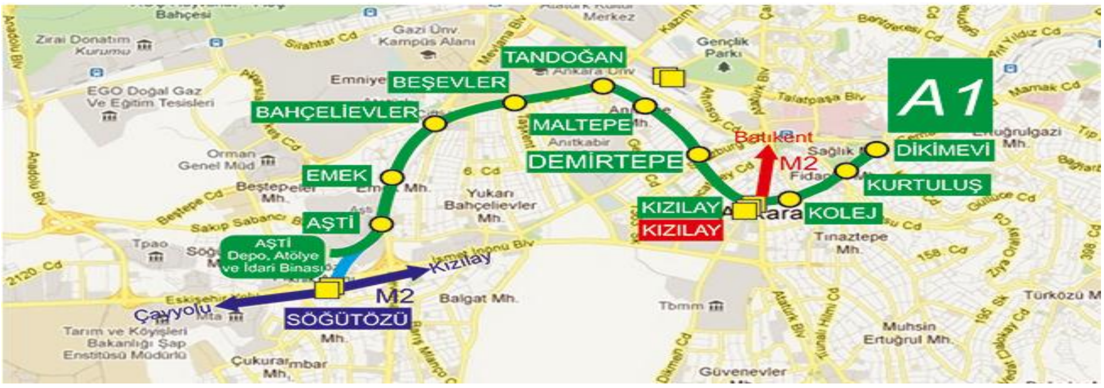


Figure 3. The rail network of Ankaray

Ankaray metro rail system has been usually used between 06.00 a.m -01.00 a.m and it operates for a total of 19 hours. It operates 5-6, 10-15 minutes interval, for peak time and for sparse time interval respectively. The targeted number of services of this system is 175 per day [24]. Ankaray rail network consists of eleven stations and has a total length of 8.527 km. The shortest distance of the line is between Anatolian and Maltepe stations and 531 meters. The longest distance is between Kızılay-Kolej stations and 977 meters. The speed limits have been taken as 18 m/sec at 350-500 meters between Demirtepe-Kızılay stations and 15 m/sec at 450-600 meters between Kurtuluş-Dikimevi stations due to the curves. The Kızılay station is where the passengers are transferred to other metro lines. Ankaray uses AEG and Breda 94 type metro vehicles. The parameters of the vehicle are listed in Table 1 [23-24]:

Table 1. The parameters of metro vehicle

Parameters	Value
Vehicle mass	40.500,0 kg
Maximum speed	80 km/hour-22.22 m/sec
Maximum acceleration (m/sec^2)	1.10 m/sec^2
Maximum braking (m/sec^2)	1.35 m/sec^2
The rated voltage	750 VDC

There is currently no measuring device to show how much energy the rail system vehicle consumes between stations. Therefore, the analyzes and comparisons have been performed by modeling and analytical method. Firstly, Case 1 has been applied and the results of practical driving have been calculated. Travel time and energy consumption values have been recorded. Then, pre-determined driving styles have been carried out and the results of all of driving styles are listed in Table 2.

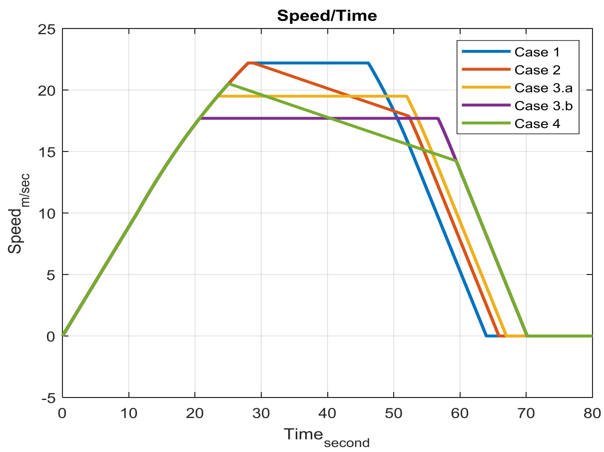
Table 2. The results of travel time and energy consumption for all cases

Stations	Length (m)	Case	Travel Time(sec)	Energy Consum.(MJ)
Aşti-Emek		Case 1	48.387	12.945
		Case 2	48.507	12.589
	608	Case 3.a (5% delay)	50.387	10.136
		Case 3.a (10% delay)	53.146	8.782
		Case 4	53.085	7.650
Emek-Bahçelievler	869	Case 1	60.162	14.903
		Case 2	61.395	12.589
		Case 3.a	62.973	12.899
		Case 3.b	65.988	11.697
		Case 4	66.048	9.979
Bahçelievler-Beşevler	798	Case 1	56.959	14.370
		Case 2	57.713	12.589
		Case 3.a	59.687	12.143
		Case 3.b	62.626	10.990
		Case 4	62.399	9.475
Beşevler-Anadolu	**804**	**Case 1**	**57.242**	**14.415**
		Case 2	57.932	12.589
		Case 3.a	60.040	12.155
		Case 3.b	62.842	11.035
		Case 4	62.806	9.518
Anadolu-Maltepe		Case 1	44.913	12.235
		Case 2	-	-
	531	Case 3.a	46.928	8.955
		Case 3.b	49.158	7.836
		Case 4	49.145	6.940
Maltepe-Demirtepe	946	Case 1	63.601	15.481
		Case 2	65.487	12.589
		Case 3.a	66.672	13.605
		Case 3.b	69.789	12.452
		Case 4	69.823	10.538
Demirtepe-Milli Irade	715	Case 1	53.192	13.748
		Case 2	53.547	12.589
		Case 3.a	55.801	11.237
		Case 3.b	58.334	10.083

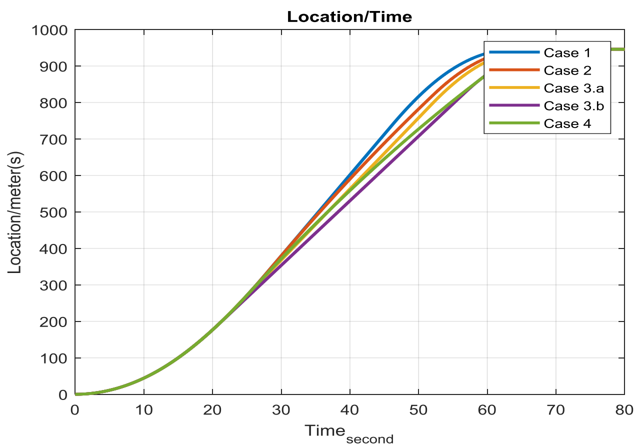
		Case 4	58.049	8.866
Milli Irade-Kolej	977	Case 1	65.013	15.713
		Case 2	67.271	12.589
		Case 3.a	68.157	13.902
		Case 3.b	71.437	12.743
		Case 4	71.143	10.911
Kolej-Kurtuluş	551	Case 1	45.789	12.518
		Case 2	-	-
		Case 3.a	48.028	9.163
		Case 3.b	50.244	8.143
		Case 4	50.229	5.825
Kurtulus-Dikimevi	950	Case 1	63.789	15.511
		Case 2	65.740	12.589
		Case 3.a	66.633	13.767
		Case 3.b	70.014	12.481
		Case 4	70.103	10.537

As you can see from Table 2, since the distance between Anadolu and Maltepe Kolej-Kurtuluş stations is very short, the rail vehicle reaches braking distance without reaching maximum speed. Therefore, Case 2 could not be applied to this part.

The speed-time, location-time and energy-time graphs of the driving of the rail vehicle between two sample stations are shown in Figure 4.a, 4.b, 4.c. respectively.



a)



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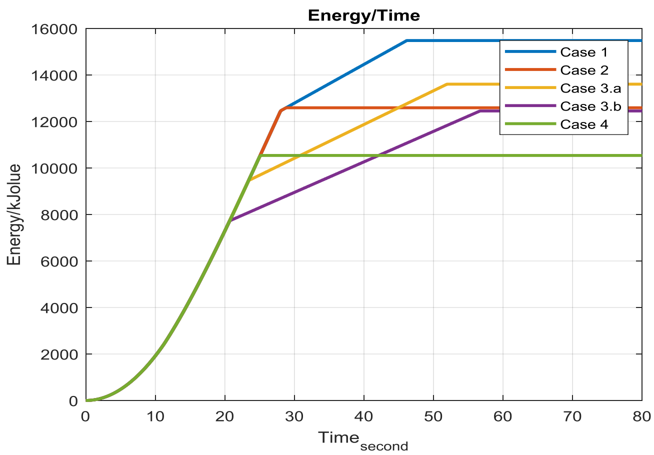

c)

Figure 4. The speed/time (a) location/time (b) energy/time (c) graph of rail vehicle's driving between for Maltepe-Demirtepe station

3. Conclusions

In this paper, the driving of the rail vehicle has been modeled, all driving phases are used and the calculations are converted from continuous time to discrete time. The effects of these phases on energy consumption and travel time have been investigated. Energy efficient driving techniques have been applied to reduce the energy consumption of rail systems and four different cases have been created depending on these techniques.

The study has not been only carried out by test data, the real data of Ankaray rail system have been used. In practical driving, the total travel time is 559.056 seconds in order to go from the start station to the end station. The amount of energy consumed for this driving is 141.839 MJ. The travel time is 568.303, 585.306, 613.578, 612. 830 seconds and the amount of energy consumed is 125.465, 116.946, 106.242, 90.239 MJ for Case 2, Case 3-a, Case 3-b and Case 4 respectively. As it can be seen, the results of the study provide energy savings of 11.54-36.37%. This savings is remarkable, and it is necessary to determine which method is chosen for good evaluation. For example, coasting driving, especially over long distances, does not increase the travel time excessively, but also reduces energy consumption considerably. Or it can be preferred both coasting driving and maximum speed reduction for sparse time operation.

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