ENERGY WISE DRIVING OF A MASS TRANSIT TRAIN

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ABSTRACT

This paper firstly gives a brief introduction to parameters that affect energy consumption of a railway system. Secondly, some related previous studies carried out by the authors will be summarized, and energy wise driving of trains and its effect on the power consumption will be examined with the help of a DC rail system simulation program.

I. INTRODUCTION

With ever increasing demand for energy and the scarcity of the natural resources has always driven the search for more reduction on energy consumption.

Mass transit systems around the world serve to the people with high energy efficiency. Although, the energy efficiency is high, the energy demand from a large rail transit network might be one of the biggest within the city it serves for.

First part of the paper will be dedicated to some of the parameters affecting energy consumption in a mass transit system. Second part deals with speed control strategies of trains to achieve better energy savings.

Traction energy is used for moving train sets on the line, and its consumption depends on many parameters including the following:

- **Line geometry**; gradients, number of passenger stations and their locations, curves, speed restrictions etc.
- **Vehicle characteristics**; control logic, weight, structure, motor, auxiliary power system etc.
- **Traction power system**; transformer substation (SS) number, locations, equipment types, feeding conductor features, feeding scheme, voltage level etc.
- **Operation concept**; frequency of train dispatching (headway time - HT), train configuration, dwell time etc.

Total consumed traction energy for a given mass transit system can be reduced by changing some of these parameters. Some of the methods that can be used for this purpose are given below:

- Reducing energy loss by catenary system paralleling [1].
- Increasing regenerated energy usage rate [2].
- Revising operation concept. Short trains with higher frequency are expected to reduce energy consumption [2].
- “Energy-wise” driving approach.
- Re-arranging speed limits on the line.

The first three methods had been examined by the authors in previous works. The last two methods will be investigated in this paper without going into much detail.

In an earlier work of the authors, it had been found that paralleling of the catenary systems can save up to 5% of total traction energy consumption [1]. After this study, the proposal of paralleling of Istanbul Aksaray-Havalimanı Metro Line catenary systems put into reality.

In another paper [2], it was showed that frequent operation does not only improve passenger convenience, but also increase energy efficiency. Therefore, using shorter trains with lower HT can be suggested for maximising the energy efficiency, as well as passenger convenience. The parameters affecting the regenerated energy usage rate were examined in that paper.

Choosing higher voltage level for power feeding configuration has important contribution to the traction energy saving. 1500 VDC voltage level for a heavy metro line can save around 10% traction energy compared to 750 VDC voltage level [3].

II. ENERGY WISE DRIVING

In normal operation train can be accelerating, cruising at an allowed maximum speed, coasting, and braking for a station or a speed restriction.

Trains run along the line according to a timetable. Timetables define the traveling time for every train from every station to station. Timetables always include some slack time for an unexpected time loss which could be caused by faulty equipment, or mostly by passengers. Slack times are also very important for punctuality which is one of the most important factors for customer satisfaction.

Station dwell times are also very important for providing punctual service. Delays are disturbing the punctual operation as well as reducing energy efficiency by consuming the slack times which can be used in normal operation conditions for energy efficient driving.

Actually, it is possible to claim that every gained second in mass rail transit operation is important. A report prepared for Istanbul Mass Rail Transit operator, Istanbul Ulasim AS (IUAS), showed that lower acceleration rate (imposed by vehicle computer) and station entrance speed limits (imposed by the signalling system) on Aksaray – Havalimani Metro line cause almost 3 minutes longer trip cycle time [4]. This extra time is almost 5% of total cycle time.

IUAS is planning to increase the station entrance speed limits on the line to 50 km/h which is 40 km/h currently. Possibilities for increasing the allowed maximum acceleration rate from 0.7 m/s^2 to 1.0 m/s^2 have also been investigated.

Optimal Speed Profile for Energy Consumption

Optimal speed profile for energy saving should be as follows:

- High starting acceleration rate,
- Optimal coasting start point with respect to timetable,
- Long coasting time,
- High deceleration rate,
- Short dwell time.

If all these principles can be applied, there could be 20-30% energy saving [5].

Nowadays, modern metro systems are mostly driven by ATO (Automatic Train Operation) systems, which are supervised and controlled by ATC (Automatic Train Control) systems. However, relatively older metro systems and LRT (Light Rail Transit) systems are usually driven by human drivers.

If the system is manual then, drivers are trained according to above given energy wise driving method. There might be some sign plates showing where they must start coasting. Such signs assist drivers to achieve higher energy efficiency. Improvements in IT, introduced more developed systems such as Driver Information Systems (DIS). A DIS stores data related to energy efficient driving, and helps the driver audio-visually.

In ATO driven systems, trains are governed by computers, and if there is a driver, (s)he only observes the operation of the train. Usually, the only job of the driver in such systems is pushing a button to open and close the doors in stations. This kind of operation isolates human errors and results in higher energy efficiency. Train coordinates can be so arranged that a braking and an accelerating train is synchronized. This synchronization increases braking energy recuperation and reduces total energy consumption.

Aksaray – Havalimani LRT system in Istanbul is a manually driven system. However, a DIS system has been recently integrated to the vehicles. Determination of optimal coasting points is still being investigated. Following sections of this paper, give first results of this project.

III. DC FED RAIL SYSTEM SIMULATION PROGRAM: SimuX

The comparison studies are done with a multi – line, multi – train simulator called SimuX [6,7]. SimuX enables the users to simulate DC fed rail systems in a user-friendly environment. It takes the regenerative braking and under-voltage behavior of the vehicles into consideration. Below given characteristics of the line are taken into account by SimuX:

1. Geometry of lines
2. Transformer Substations
3. Trains (Different types possible)
4. Passenger stations
5. Depots
6. Isolation points (Section Insulators)
7. Jumpers (Conductive connection between catenary wires or rails)
8. Traffic lights
9. Rail Potential Control Devices – RPCD
10. Coasting regimes.

The simulator has been used in many major modification projects which are carried out for IUAS. It has also been used for many new line traction power system design works such as Uskudar – Umraniye Metro, Sultanciftligi – Vezneciler – Topkapi Metro, and finally Kirazli – Basaksehir – Olimpiyat Koyu Metro Lines.

IV. TEST SYSTEM

Aksaray – Havalimani Metro line characteristics were used for all the simulation tests. Main features of the line are given below:

Length: 19 km
Trains: 4 cars (all with motor), 92 m.
Passenger stations: 17
Transformer Substations (SS): 9
Nominal voltage: 750 VDC, Catenary system

Catenary Resistance per km: 44.4 mΩ
Track Resistance per km: 20.6 mΩ
SS Ratings: 2 x 2400 kVA

Tractive effort produced by one vehicle versus speed diagram is given in Figure 1.

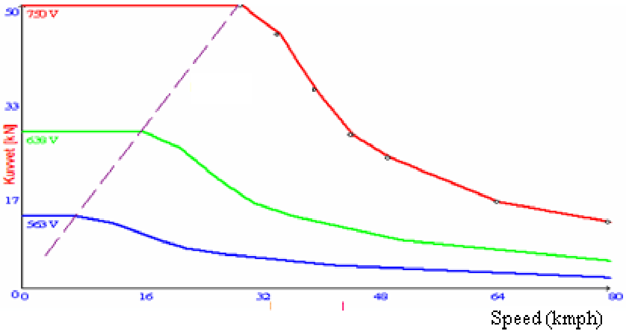


Figure 1. Tractive effort (kN) – Speed (km/h)

Several simulation tests were carried out to investigate the effect of coasting and maximum speed.

V. SIMULATION TESTS

Total energy consumed by the system depends on many parameters as indicated above. In this section, the effect of two important parameters (namely speed limit of the line and coasting strategy) on energy consumption is examined.

Firstly, the normal case, where maximum speed is 80 km/h and there is no coasting scheme is simulated. Then, speed limit is reduced to 70 km/h, and simulation is repeated. Lastly, a couple of basic coasting schemes tested.

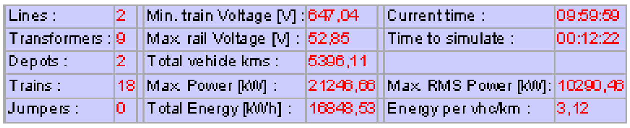
All simulation tests are carried out with 180 second headway time between the trains.

Normal Case Test

Trains are allowed to accelerate up to 80 km/h where there is no speed restriction imposed by civil works. When trains reach this predefined speed limit, they try to keep their speed at 80 km/h. They do not coast. This type of operation is called as all-out operation, and it is the best to achieve highest commercial speed on the line. However, it is possible to show that this way of driving is less energy efficient in comparison to schemes that allow coasting.

Results for this simulation are summarized in Table 1.

Table1. Normal Case Test Results



Lines :	2	Min. train Voltage [V] :	647,04	Current time :	09:59:59
Transformers :	9	Max. rail Voltage [V] :	52,85	Time to simulate :	00:12:22
Depots :	2	Total vehicle kms :	5396,11		
Trains :	18	Max. Power [kW] :	21246,66	Max. RMS Power [kW]:	10290,46
Jumpers :	0	Total Energy [kWh] :	16848,53	Energy per vhc/km :	3,12

Traction energy consumption per Vehicle per km is calculated as 3.122 kWh. Trip cycle time is calculated as 00:53:46. This time does not cover the dwell times in first and last stations. Two values that are to be compared with other test results are given below:

Total trip cyle time (s): 3226
kWh/(Veh * km): 3.122

A speed vs. location graph for a train traveling from Aksaray to Havalimani is given in Figure 2. Figure 3 shows a close-up graph for this profile.

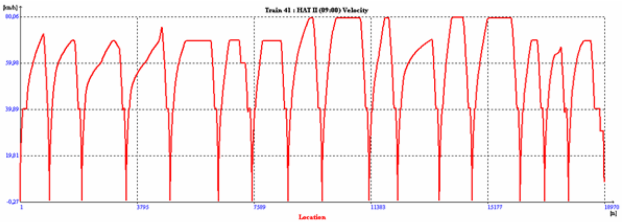


Figure 2. Speed vs. Location Profile for a train in normal operation

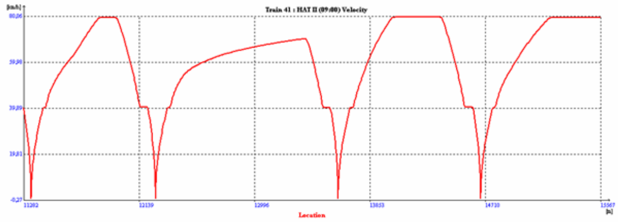


Figure 3. Close – up Speed vs. Location Profile for a train in normal operation

It can be seen from the Figure 2 that trains can not reach to maximum speed of 80 km/h in most of the trip time. The reason for this could be gradients, vehicle characteristics, and speed restrictions on the line. Speed restrictions arround passenger stations can be seen very clearly in Figure 3, which gives a closer view of the speed profile.

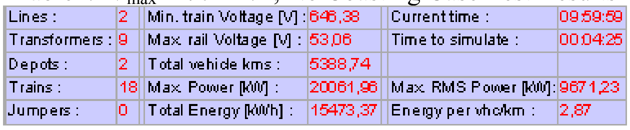
V_{max} = 70 km/h, No Coasting Case

Speed limits on each section of the line are pre-determined according to the alignment conditions. Signalling system controls the train speed at all times, and if the allowed speed is exceeded by a small margin, emergency brakes are applied to train until it is halted.

Taksim – 4 Levent metro line is driven by ATO. ATO commands trains to go at lower maximum speeds during off-peak hours which gives lower energy consumption values.

A simulation test is carried out to understand what would be the energy consumption, if a similar approach applied to Aksaray – Havalimani metro line operation, too. The simulation test is repeated with reduced maximum speed of 70 km/h. Results are summarized in Table 2.

Table2. V_{max} = 70 km/h, No Coasting Case Test Results



Lines :	2	Min. train Voltage [V] :	646,38	Current time :	09:59:59
Transformers :	9	Max. rail Voltage [V] :	53,06	Time to simulate :	00:04:25
Depots :	2	Total vehicle kms :	5388,74		
Trains :	18	Max. Power [kW] :	20061,96	Max. RMS Power [kW]:	9671,23
Jumpers :	0	Total Energy [kWh] :	15473,37	Energy per vhc/km :	2,87

Two values that are to be compared with other test results are given below:

Total trip cyle time (s):	3267
kWh/(Veh * km):	2.871

Above given values confirm the expected result: While the trip cycle is longer, the energy consumption is lower compared to the normal case.

A speed vs. location graph for a train travelling from Aksaray to Havalimani is given Figure 4.

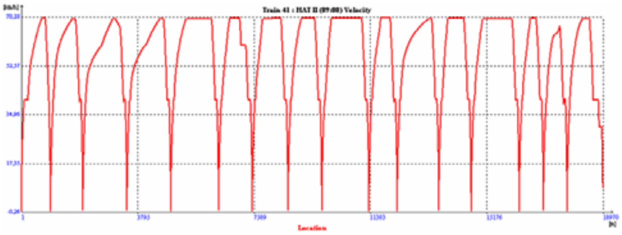


Figure 4. Speed vs. Location Profile for a train with reduced speed limit

It can be seen from Figure 4 that trains can reach to maximum speed of 70 km/h almost at all acceleration regions.

Examination of Coasting Schemes

Under this operation condition trains are commanded to coast at pre-determined locations or speeds. Depending on the line alignment, determination of these points and speeds optimally requires solution of a huge solution space.

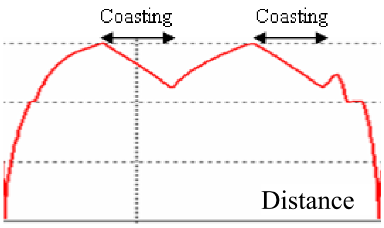


Figure 5. Coasting scheme

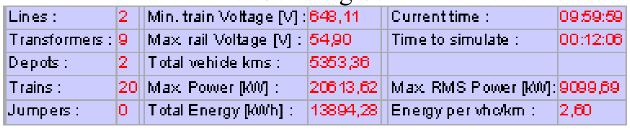
Figure 5 gives general characteristics for a coasting scheme. There is generally a coasting start speed, V_C. It is not desirable that the trains slow down too much during coasting, so a re-motoring speed, V_{RM}, is also defined. Moreover, It can be required that trains do not start coasting before a predefined distance, which is denoted as V_{CL}.

Coasting Scheme 1: V_{max} = 80 km/h V_C = 60 km/h, V_{RM} = 45 km/h, V_{CL} = 250 m

In this set up, trains start coasting after 250m they leave the station, if their speed reached 60 km/h. Trains slow with resistance forces down to 45 km/h. If this occurs, trains re-motor with maximum acceleration rate. Therefore, if the station to station distance is long, this pattern is repeated many times, until the train brakes to stop at a passenger station.

Naturally, if the gradient is negative, i.e. train is going down a slope, train continues to speed up even it starts to coast after 60 km/h. It will speed up with its potential energy until it reaches the civil speed limit, which is V_{max} = 80 km/h. Results for this test is summarized in Table 3.

Table 3. First Coasting Scheme Results



Lines :	2	Min. train Voltage [V] :	648,11	Current time :	09:59:59
Transformers :	9	Max. rail Voltage [V] :	54,90	Time to simulate :	00:12:06
Depots :	2	Total vehicle kms :	5353,36		
Trains :	20	Max. Power [kW] :	20613,62	Max. RMS Power [kW]:	9099,69
Jumpers :	0	Total Energy [kWh] :	13894,28	Energy per vhc/km :	2,60

Two values that are to be compared with other test results are given below:

Total trip cyle time (s):	3397
kWh/(Veh * km):	2.595

When these results are compared with the results of normal case, it can be seen that a very high energy saving is achieved, but trip time is also increased drastically. It can be observed from Figure 6 that this would not be a very comfortable journey for the passengers.

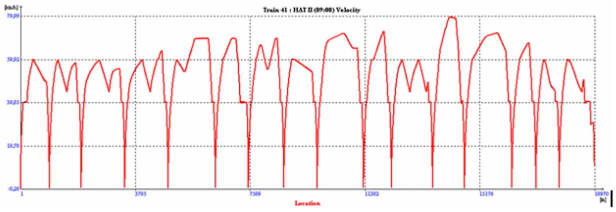


Figure 6. Speed vs. Location Profile for a train with the first coasting scheme

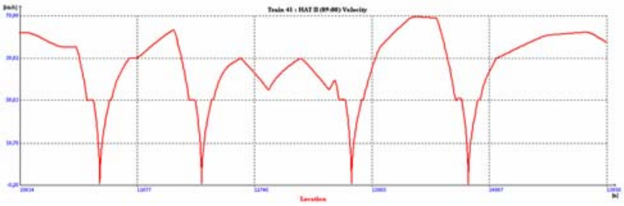


Figure 7. Zoomed-in view of Speed vs. Location Profile for a train with the first coasting scheme

Figure 7 shows that accelerating train reached to the speed of 60 km/h at 12650 m, where it starts to coast. The coasting train re-motors when the speed drops below 45 km/h. This cyle repeated once more. When train was trying to accelerate for the 3rd time it had to brake since it was approaching the station speed limit zone. In 6 regions, trains are forced to re-motor. This shows that for an optimal and comfortable journey, either V_C must be increased, or V_{RM} must be reduced for these regions.

An opposite situation occurs around 13850 m where coasting train speeds up and reaches the maximum allowed speed limit on that zone. There is -3.38% gradient in that region, and therefore, the coasting train continues to speed up until 70 km/h. When train reaches to this speed limit, it brakes slightly in order not to exceed this speed limit. Figure 8 shows this event more clearly.

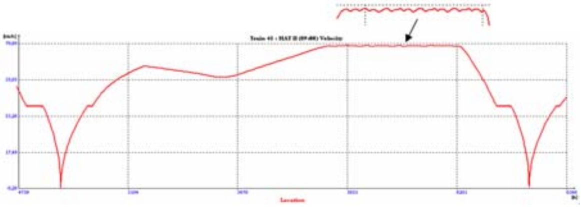
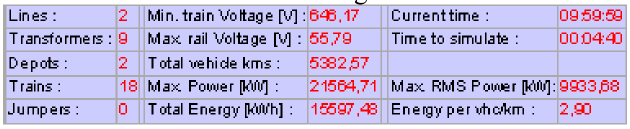


Figure 7. Zoomed-in view of Speed vs. Location Profile for a train with first coasting case

Coasting Scheme 2: V_{max} = 80 km/h, V_C = 70 km/h, V_{RM} = 50 km/h, V_{CL} = 400 m

Parameters related to coasting scheme is altered as per title, and the simulation test is repeated. Results are given in Table 4.

Table 4. Second Coasting Scheme Results



Lines :	2	Min. train Voltage [V] :	646,17	Current time :	09:59:59
Transformers :	9	Max. rail Voltage [V] :	55,79	Time to simulate :	00:04:40
Depots :	2	Total vehicle kms :	5382,57		
Trains :	18	Max. Power [kW] :	21564,71	Max. RMS Power [kW]:	9933,68
Jumpers :	0	Total Energy [kWh] :	15597,48	Energy per vhc/km :	2,90

Two values that are to be compared with other test results are given below:

Total trip cyle time (s):	3260
kWh/(Veh * km):	2.898

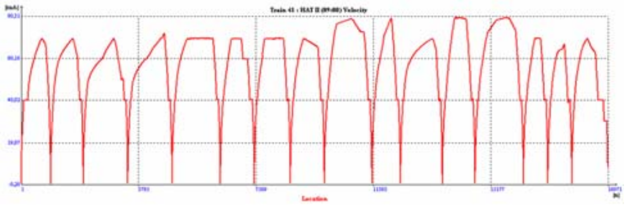


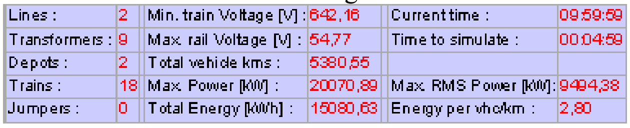
Figure 8. Speed vs. Location Profile for a train with the second coasting scheme

Figure 8 gives the train speed-location profile for this scheme. This graph shows that the operation is more smooth in comparison to the previous scheme.

Coasting Scheme 3: V_{max} = 70 km/h, V_C = 70 km/h, V_{RM} = 40 km/h, V_{CL} = 500 m

One last test with altered parameters relating to coasting scheme simulation test is repeated. Results are given in Table 5.

Table 5. Third Coasting Scheme Results



Lines :	2	Min. train Voltage [V] :	642,16	Current time :	09:59:59
Transformers :	9	Max. rail Voltage [V] :	54,77	Time to simulate :	00:04:59
Depots :	2	Total vehicle kms :	5380,55		
Trains :	18	Max. Power [kW] :	20070,89	Max. RMS Power [kW]:	9494,38
Jumpers :	0	Total Energy [kWh] :	15080,63	Energy per vhc/km :	2,80

Two values that are to be compared with other test results are given below:

Total trip cycle time (s):	3286
kWh/(Veh * km):	2.803

Comparison Table of Tests

Two values for the comparison are summarized for all the tests done are given in Table 6.

Table 6. Comparison table for all simulation tests

Explanation	Normal Cases		Coasting Cases		
	V_{max}=80	V_{max}=70	60-45-250	70-50-400	70-40-500, V_{max}=70
Total trip cycle time (s)	3226	3267	3397	3260	3286
kWh/(Veh*km)	3,122	2,871	2,595	2,898	2803
Difference on time (%)		1,27	5,30	1,05	1,86
Difference on energy (%)		-8,04	-16,88	-7,17	-10,22

The last row of the Table 6 gives the difference between the normal case, which is the fastest, but with the most energy consuming. While the last row gives energy saving percentage compared to the normal case, one upper row gives the trip time increase in percentage.

Reducing the allowed maximum speed to 70 km/h gives 8% energy saving, while increasing the trip time only 1.27%.

Table 6 shows that the first coasting scheme results in approximately 17% saving on energy. However, trip cycle time increases by 5.3%. This increase corresponds to 3.18 minutes for 1 hour trip cycle time. This means that it is required to put one more train on the line to achieve same level of service HT, which can not be acceptable.

In case of coasting between 70-50 km/h, trip cycle time increases only by 1%. This increase corresponds to 37 seconds for 1 hour trip cycle time. Energy saving for this case is 7.2%.

The last coasting test where allowed maximum speed is reduced to 70 km/h causes 67 seconds increase in trip cycle time, while reducing energy consumption by 10.2%. Aksaray – Havalimani line has 17 stations, which means trains are stopping 32 times along the line during one trip cycle, in addition to terminal station wait times. Therefore we believe that 67 seconds can be easily covered with station dwell-time control.

As it can be understood from these few tests that for determining the optimal coasting points, many more simulation tests must be carried out. There is an ongoing research in this direction.

VI. SUMMARY and RECOMMENDATIONS

In this paper, previous studies carried out by the authors related to energy efficiency in mass rail transit systems are summarized. Previous works had covered many aspects from energy loss reduction measures in power supply system to vehicle related parameters affecting energy consumption of the system. However, train driving techniques and especially the maximum speed limit and coasting regimes, and their effect on the energy consumption level explored with some basic tests for the first time in this paper.

Energy wise driving techniques add on more energy saving over what can be achieved by fixed installation measures such as choosing higher voltage level, power supply system feeder paralleling.

Simulation tests showed that allowed maximum speed restriction has quite important impact on the energy consumption level. This value must be chosen optimally taking into account for vehicle characteristics, and line alignment features.

Applying coasting regimes for the train speed profile gives the best energy saving values. Basic tests showed that up to 17% energy can be saved with a trade-off in travel time. Coasting regime study must be carried out for every new line before putting them into commercial service.

However, choosing the right parameters for coasting regime is very important. Global optimization of these coasting parameters for a whole line against trip cycle time is a daunting job, since an exponentially growing number of alternatives need to be studied. The authors propose the use of artificial neural networks and genetic algorithms for this purpose, and very first results suggest a promising future for such an approach.

VII. ACKNOWLEDGEMENTS

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