Improvements of energy efficiency of urban rapid rail systems

S. Oettich, T. Albrecht & S. Scholz
“Friedrich List” Faculty of Traffic and Transportation Sciences, Dresden University of Technology, Germany

Abstract

In general, there are three complementary approaches to energy reduction in urban rail systems operation, such as rapid rail or metro.

Firstly, the driving style and timetable of a single train run can be adjusted, so that traction energy consumption is minimal. To implement this strategy in manually operated systems an assistance system would be necessary.

Secondly, the use of energy regenerated during braking in the railway network contributes to a further reduction of overall energy consumption. To influence the amount of regenerative energy used by other trains, the optimal choice of the synchronization time between the departures in the two directions is necessary as well as train running time control.

The third approach presented deals with strict adaptation of transport supply to demand by using small vehicles and flexible headway scheduling. The operational effort of the railway system can be reduced for a constant or even increasing traffic demand, so that the required traction energy is minimized.

An estimation of the potential energy reduction is presented for each strategy by means of simulation and case studies.

1 Introduction

In the project “intermobil Region Dresden”, a major research project funded by the German Federal Ministry of Education and Research, new and intelligent strategies in vehicle control were developed, to reduce the energy demand of urban railway operation. In this paper three complementary strategies are described:

1. The energy-efficient driving of a single train along a railway line by energy-optimum adjustment of driving style and timetable,
2. Efficiently using regenerated energy from braking, and
3. Adaptation of transport supply to demand.
These strategies can be put in an order according to the efforts needed for their implementation (cf. Figure 1) and form a hierarchic model of optimized train control in urban railway operation.

Figure 1: Three complementary strategies for energy saving in urban railways.

2 Energy-optimum adjustment of driving style and timetable

The task to be solved at this stage can be formulated as follows: A train shall travel along a railway line with multiple stops within a given time in such way that the costs of the journey – which are to be further specified – are minimized.

The solution for this task has been published earlier [1], therefore only the main ideas will be presented here.

2.1 Timetable adjustment for a single train run

The adjustment of the timetable is done by optimally distributing the time reserve $t_R$ of the train, that is the difference between scheduled and minimum running time of the train to the terminus, over the remaining sections of the journey. This task can be formulated as a multi-stage decision process. The method of Dynamic Programming by Bellman [2] is an appropriate tool for solving this problem.

The costs of the journey can be calculated by considering two quality criteria:
1. The amount of traction energy consumed by the train during the journey.
2. The total waiting time of passengers missing connections to and from road-bound means of public transport, and
In order to find the best solution at each stage and state, a multi-criterion decision problem has to be solved.

2.2 Adjustment of driving style between two consecutive stations

The basic solution for energy-optimum driving is fairly simple and consists of a sequence of four phases [3]:

1. Speedup with maximum allowed acceleration,
2. Driving with maximum allowed speed,
3. Coasting with motors turned off,
4. Braking with maximum allowed deceleration.

But choosing the right time to switch from one phase to the other so that the timetable is respected, is virtually impossible for a human driver. But the optimum driving regime can be calculated within a state space formed by the position of the train (measured as distance to the next stop), the speed of the train and the time remaining until next stop [1, 3].

2.3 Driving advice system

To assist the driver in the task of energy optimum train control, an advice system is needed that is continuously monitoring the position and speed of the train. (If there is an ATO for train control, the described algorithm can be integrated within.) It calculates the optimum driving regime and outputs this information to the train driver.

The advice system is equipped with an automatic vehicle location component using GPS signals and odometry information, and GSM-R radio to transmit arrival and departure time information of road-bound vehicles to be used in timetable optimization.

To estimate the amount of energy saved, extensive tests were carried out using a driving simulator. Figure 2 illustrates some results of this study: One journey at a example line with manual driving, and another one using the advice system. The duration of both runs was equal, but one can notice the lower maximum speed of the second journey. The mean energy consumption of all simulated journeys at the example line is about 7% lower when using an advice system.

3 Efficiently using regenerated energy from braking

In a UITP survey of subway operators [4] it was estimated that taking the energy absorption from the train as reference 42% of it is kinetic energy set free during braking. In electric railway systems, the best way of using this braking energy is to feed it back into the power supply network so it can be used there by other trains drawing power at the same instant.

Due to the fact that the network is not always able to absorb this energy, only about two thirds of this energy can actually be used by other trains. If and how
the remaining energy can be used by only modifying the train’s timetable shall be examined here.

At first, the effects of the electric power supply system on the use of regenerative energy have to be considered. Then, the influence of the timetable is examined closer by means of a case study.

3.1 Effects of the electric power supply network on energy consumption

During the transmission of electrical energy from the substations to the trains two effects must be taken into account, that have major importance for the amount of energy to purchase:

1. Regenerative energy can only be feed into the network, when it can be consumed therein.
   But DC networks are in most cases coupled to AC utility supply by rectifier substations [4], so it is not possible to transmit power back to the utility supply. When no consumers are available within the concerned part of the network, regenerative energy must be dissipated in braking resistances. This energy has to be regarded as lost energy for the operator.

2. When a train is demanding electrical power for traction, the current causes voltage drops over the catenary, which induce higher currents and therefore higher electric energy consumption. This problem is especially critical in DC systems where system voltages are much lower than in AC systems.

3.2 Influence of the timetable on energy consumption

It can be shown that the headway itself and the synchronization time between the two directions (see Figure 3) do influence energy consumption the most.

In Figure 4, one line of the DC-electric Berlin S-Bahn is analyzed. In the left diagram (a), the influence of the headway on energy consumption was examined tak-
ing into account only the vehicles travelling in one direction. The energy-optimal timetable for the single train was used as proposed in section 2. System energy consumption increases with increasing train headway because of less regenerative energy used.

Introducing the second direction of movement, the amount of regenerative energy absorbed by other trains also depends on the synchronization time. For the selected case of a 10-mins headway the potential for energy saving by modifying synchronization time is 11% as can be seen from Figure 4b.

3.3 Use of regenerative energy – a problem of timetable optimization

Headway and synchronization time can rarely be fixed in favour of energy consumption but have to meet constraints of traffic demand (headway) and operation (no. of trains, connections to other lines, etc.).
In situations of given headway and synchronization time where large amounts of energy are being wasted in braking resistances (e.g. 180 s synchronization time for a headway of 600 s in figure 4b), the modification of train running times on the sections of the line can contribute to reducing energy consumption.

The algorithm proposed in [5] is based on the application of Genetic Algorithms (GA). It computes a solution for a distribution of train travel time reserve along a line for both directions simultaneously. The cost function can be fixed voluntarily, here, system energy consumption was used, the results are also plotted in Figure 4b. For the selected example energy saving potential by train running time modification is in the order of 4% for bad synchronization times whereas with good synchronization times the additional potential of running time modification is almost negligible.

Other studies have shown, that the potential for energy saving by modifying synchronization times sometimes exceeds 20% but reaches 10-15% on average. The amount of energy to be saved by train running time control may climb up to 10% in situations of a bad combination of headway and synchronization time.

In general, it is favourable to choose an optimal combination of headway and synchronization time for the timetable with minimal energy consumption for the single train. For this case a controller exists, by which energy consumption can be minimized and, at the same time, the timetable’s inherent coordination property contributes to a good usage of regenerative energy. For other situations, train running time modification can lead to a better usage of regenerative energy but this effect can only be realised in practical operation when station dwell times vary slightly in the order of a few seconds.

4 Adaptation of transport supply to demand

In medium-sized conurbations with 0.5 to 1.0 mill. inhabitants urban rapid rail transit lines usually offer train headways from 15 to 30 minutes, using a traditional fixed interval timetable with some extra trains during the peak hours. Large trains are used and the train headway is chosen in order to serve demand at the peak hour. But in this case a large overcapacity is provided during off-peak hours, resulting in a low average occupancy rate. Since the offered capacity, namely the operational effort $b_l$ (measured in place-kilometre), is proportional to the traction energy consumption $E$ of rapid rail transit systems (cf. Fig. 5b and [4]) the consumed energy is higher than required.

4.1 Demand-driven control of transport supply

The basic approach of demand-driven operation is characterised by the control of the train headway $T_s$ in such a way that transport supply is adapted to demand as much as possible (cf. Fig. 5a). This operating strategy allows to reduce overcapacity, namely operational effort $b_l$, in comparison to the traditional operation.

In order to evaluate the adjustment of supply to spatio-temporal variations in passenger demand the so called traffic efficiency is used. Traffic efficiency is de-
Figure 5: Demand-driven train operation of the System VAL in Lille [6] and traction energy consumption of underground railway systems [4].

Defined as the ratio between traffic performance \( vl \) (characterized by passenger-kilometres) and operational efforts \( bl \) expressing an average occupancy rate.

The best German urban rapid rail transit systems reach a traffic efficiency between 17% and 18%. The demand-driven operating strategy of existing rapid transit systems (e.g. VAL in Lille, Lyon metro Line D) increases traffic efficiency up to 34% [7, 8]. The energy consumption is considered to be very sensitive to the occupancy rate [9].

The transport supply which is determined by the train headway and the vehicle size \( CV \) (regarding a maximum load factor \( \gamma \)) can be adjusted to demand by choosing the optimal train headway \( TS \). Accordingly, the deviation \( \varepsilon_{VAG} \) between supply and demand shall become minimal at the heaviest loaded section of a line.

\[
\varepsilon_{VAG}(t, TS) = \frac{CV \cdot 60}{TS} \cdot \gamma - VA(t, TS) \rightarrow \text{MIN} \geq 0. \tag{1}
\]

Furthermore the train headway is restricted to an upper bound \( TS, max(t) \) in order to offer a minimum service quality.

### 4.2 Estimation of supply-demand response

For the solution of eq. (1), a transport demand model is required in order to estimate the traffic load \( VA(TS) \) [10].

An aggregated transport demand model was developed which allows to obtain explicit equations for the optimal train headway taking into account the supply-demand response [7, 8], because the use of a disaggregated transport model would lead to a time-consuming iteration process to find the optimum headway \( TS \). With this model a direct relationship \( F \) between alteration of supply and alteration of
demand can be identified. An off-line scheduling strategy (cf. Figure 6) can be
derived, minimizing operational effort $bl$.

\[
T_{S,\text{opt}} = f(t, C_V, T_{S,\text{min}}, T_{S,\text{max}}, F) \\
VA(t, T_S) = F(t, T_{S,\text{opt}})
\]

Figure 6: Basic principle of a demand-dependent scheduling strategy.

4.3 Efficiency of demand-driven operation

The dependency of transport demand and supply against the train headway $T_S$ is
illustrated in Figure 7 for a medium-sized conurbation with a about 0.78 mill. in-
habitants, which approximately corresponds to the city of Dresden and its suburbs.
If there is an interception point between demand and supply curve the deviation
according to eq. (1) is zero. Overcapacity is not produced and the operational effort
$bl$ meets demand. As it is clearly to see from Figure 7 the vehicle capacity $C_V$ has
tremendous influence on the supply-demand equilibrium. If the vehicle capacity
exceeds a certain value this equilibrium cannot be achieved at all ($C_V \geq 1000$).

The current train operation of the urban rapid rail transit line of the city of Dres-
den provides train headways of 15 (peak) and 30 minutes (off-peak) using a ve-

Figure 7: Conditions for demand-dependent controllability of transport supply.
vehicle with capacity $C_V = 1000$ and has a low traffic efficiency (occupancy rate) of about 12%. By turning the fixed interval timetable into a demand-dependent train operation with a vehicle capacity $150 \leq C_V \leq 250$ it could be improved to about 31%, reaching the efficiency of existing demand-driven operated rapid transit system (cf. Figure 7). The traffic performance would increase to 170%, the operational effort decreases to 75% (cf. Figure 8a). Despite of an increased number of trains per day the overall traction energy consumed decreases to about 76% of the current value (cf. Figure 8b).

If a fixed interval timetable with 7.5 (peak) and 15 minutes (off-peak) headway was used a vehicle capacity of 500 places would be required. In this case a demand-dependent train operation would lead to about 20% energy reduction and a traffic efficiency of 31%, too.

Interestingly, there is a global minimum for both $bl$ and the traction energy $E$ (cf. Figure 8a). But the traffic efficiency rises even when using smaller vehicles. Since the traffic efficiency evaluates the overall performance (in terms of an average load factor) the best vehicle capacity for overall efficiency need not be equal to that for minimum energy consumption.

5 Conclusions

In this paper a hierarchic control strategy was presented to reduce energy consumption in urban railway operation. The energy savings, that were estimated by means of simulation in case studies, are compiled in Table 1.

In summary it may be said the first and second strategy proposed offer a minor reduction of energy consumption and can be implemented easily. Since the use of a smaller vehicle is mandatory for the success of the third strategy, it is more complicated to introduce although offering the highest potential of energy reduction.
Table 1: Energy savings estimated by means of simulation in case studies.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Energy-optimum adjustment of driving style and timetable</td>
<td>7–10 %</td>
</tr>
<tr>
<td>2. Efficiently using regenerated energy from braking</td>
<td>5–10 %</td>
</tr>
<tr>
<td>3. Adaption of transport supply to demand</td>
<td>20–25 %</td>
</tr>
</tbody>
</table>

Acknowledgements

The results described in this paper where gained in the research project “intermobil Region Dresden”, funded by the German Federal Ministry of Education and Research (contract no. 99 B 9907 A8) as part of the research program “Mobility in Conurbations”. The authors would like to thank Prof. H. Strobel for the support and valuable advice given during the elaboration of this paper.

References