Application of Vehicle-to-Infrastructure Networks in Vehicle Control and Monitoring Systems

Overview of Ph.D. Thesis by

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1 Introduction

Demand for transportation is continuously increasing in the European Union resulting in an increase in the energy consumption of the sector. The global challenge is to make transportation more efficient and environmentally friendly. Owing to the rapid development of microelectronics and mobile telecommunications at the end of the '90s a wider range of fleet diagnostics and satellite tracking have became available. These innovations provided a technological background for the creation of on-line telemonitoring systems. Economic demand for telemonitoring systems rose as a consequence of the increased competition in passenger and freight transport especially in road traffic. Nevertheless an on-line telemonitoring system integrated with a modern ERP system (which naturally considers the special requirements of the rail transport) could improve the efficiency of a rail traction company. In addition the savings can be increased with the introduction of the electronic documents.

During my research I have dealt with road and railway information systems. The methods presented in my thesis can solve special problems in the railway remote monitoring systems and offer several options for further development.

I used a vehicle-side approach addressing the vehicle as a source of data and started to examine the solutions in the field of road transport. The aim was the development of a complete remote monitoring system intended to deal with the architectural issues, communication technologies and server-side load issues. After the design of the system it was important to examine the usability of the data for the derived high-level functions. This area is also very sparse, as virtually the entire railway operation, as well as accounting, marketing and controlling functions can be supported. From these possibilities I chose the individual vehicle control issues as some of the most relevant issues of train operation, only after the safety aspects. Furthermore the Hungarian State Railways do not use any driver advisory system, neither do they encourage economical driving, or deal with this topic in the training of the engine drivers. This is the reason why I addressed this topic as my research interest.

The first part of my research deals with the application possibilities of remote monitoring systems for railway examining the benefits of the introduction of such a system. Through the example of the Hungarian State Railways I present the positioning of the monitoring system within the railway IT system. Communication with the vehicles must meet several quality requirements including availability, response time or safe recovery after a possible shutdown, etc.; which imposes strict requirements on the system's server application. Thus in addition to careful planning - for which a possible structure is introduced - the control of the service is needed, which can be handled using control theory [1],[2], naturally at the presence of an appropriate queuing model [3]. In IT systems most of the state variables can be measured directly, although in many cases system load requires estimation [4]. To solve this problem I modelled the system as a M/G/1 type queuing model and designed a state-feedback control system.

Locomotive on-board computers with network access can serve not only the communication needs of the engine and the driver, but can also act as a gateway to serve the entire train telemetry subnet and support - including but not limited to - the maintenance or even passenger information [5] tasks. However, train composition is not constant, and - with the exception of the newer types of carriages - free-to-use wires inside the remote control cables are not provided. The next part of the thesis deals with wired networks issues of the trains without the so-called "intra-train" network in special circumstances and harsh environments [6]. However the implementation of the digital data transmission on a non-standard communication is an important problem to be solved to maintain the appropriate levels of the network quality parameters. First the non-standard solutions were tested under laboratory conditions. In addition I proposed an appropriate sectioning solution to detect the variable network topology and designed an algorithm to control the detection process. This will ensure the communication possibility via the free wires of the train remote control cable. The developed methods were validated on real trains both in stationary and moving states.

The availability of on-line and real-time information opens a huge opportunity for increasing the efficiency of the railway operation. The optimization of the operation of the railway system can reduce delays caused by the unique chain-reaction-like delay propagation and helps to restore the normal operation. In addition it can help the energy optimization of the individual train movements [7], [8], [9].

The last part of my thesis focuses on the examination of the traction energy consumption between two stations. To achieve this the real-time telemetry data provided by the monitoring system are essential, so the available journey time can be determined, but it is also necessary to know the speed limits and the slope conditions of the relevant section. The task includes two conflicting criteria, which keep the journey time and minimize energy consumption. I have developed a solution to apply predictive optimization, which has induced some further problems to be solved.

The first task was the determination of the propulsion resistance of longitudinal train dynamics. I applied the polynomial function of the resistance force found in the relevant literature [10],[11],[12]. To determine the parameters I used on-board engine data with one-second sampling time and proved that the parameters can be well estimated without additional special measurements.

To ensure the time-keeping property of the predictive optimization it is essential to generate a reference run [13], which keeps the required journey time, thus the optimization algorithm can follow it on the prediction horizon as a constraint. For this purpose a formerly recorded train run can be used or it can be generated with a suitable algorithm [14] [15]. I developed two optimal speed profile generator algorithms, which consider the entire section and the journey time. The first one is simpler with less processing requirements, but it ignores the inclinations of the track, while the second method extends it with the slopes at the cost of higher computation demand.

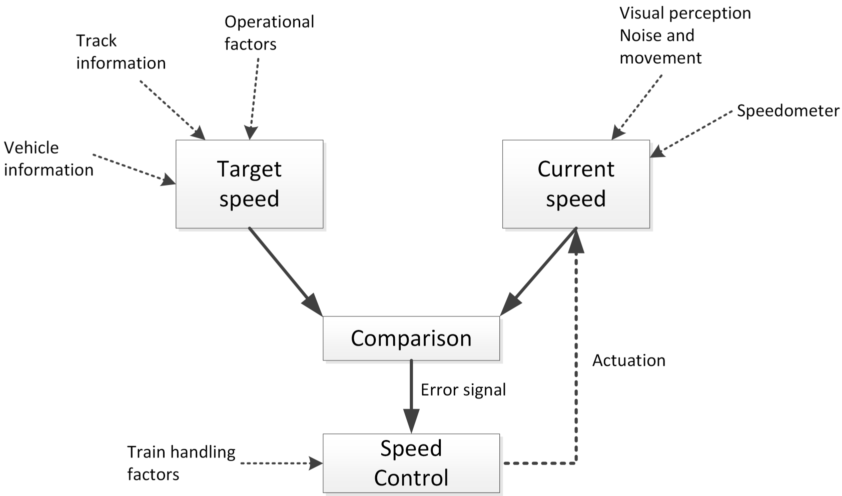


Figure 1: Human speed control process

The final goal was to develop a driver advisory system which can support energy optimal driving (Fig. 1) by providing real-time speed recommendation to the engine-driver. Fundamentally a pre-calculated, static speed profile could be essential, but it can not be actuated by the driver in all cases, thus the optimal profile may become obsolete. During the journey the continuous optimization is expedient which can be achieved by the proposed predictive control system.

2 Contributions of the Thesis

Thesis I.

I have designed a control method for the communication subsystem of a telemonitoring system based on the needs of rail transportation represented as a queueing model, taking its load and service time into account. The method controls the linear constrained system model switching between different state-feedback control schemes based on the estimated load.

Related publications: [Ara07],[AB08],[BA08],[BA10],[BA09]

- I have defined the roles of the interface subsystem responsible for the communication with the vehicles as a result of the examination of the IT architecture of the railway management systems.
- I have designed a communication model structure able to serve the complex needs of the railway telemonitoring systems, in particular the needs of reliability and modularity.
- I have pointed out the importance of the performance-control of the server application considering the limited computational resources.
- I have elaborated the linear state space representation of the system which, considering random arrival process and stochastic service time, acts as a M/G/1 type queueing model. The discrete linear form of the model is the following:

$$x(n+1) = Ax(n) + Bu(n) \tag{1}$$

$$y(n) = Cx(n), \text{ where} \tag{2}$$

$$x = \begin{pmatrix} x_{proc} \\ x_{serve} \\ x_{ql} \\ x_{cln} \end{pmatrix}, \qquad u = \begin{pmatrix} u_{serve} \\ d_{ri} \\ d_{clo} \\ d_{cli} \end{pmatrix},$$

$$A = \begin{pmatrix} 0 & c_{serve} & 0 & c_{ekp} \\ 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad B = \begin{pmatrix} 0 & c_{ib} & c_{cico} & c_{cico} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 1 \end{pmatrix}$$

$$C = \begin{pmatrix} 1 & 0 & 0 & 0 \end{pmatrix}$$

- I have designed two control schemes for the model (Figure 2), one for the keeping of the cycle time of the service for overloaded situations, and an other for normal operation. I have chosen a model-based estimation of service time based on continuous measurement and filtering. The switching between the different control schemes utilizes a hysteresis rule for the estimated load value.

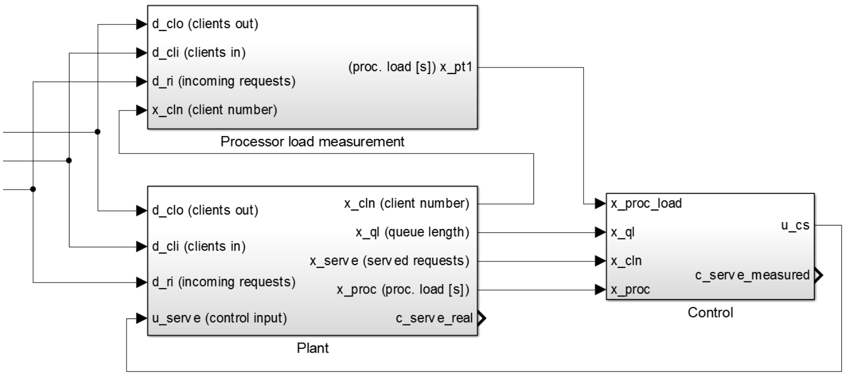


Figure 2: Schematics of the control architecture

Thesis II

I have proposed a design of an intra-train network for vehicles equipped with a telemonitoring system, which considers the environmental disturbances and the variable network topology, ensuring a reliable communication channel between the on-board units.

Related publications: [ABG13a],[ABG15b]

- I have examined the different digital communication technologies capable of transferring data on long-distance wired media and chosen the one, which seems to be the most appropriate for the inspected environment.

- I have defined the effects of the non-standard media and termination resistance values on the performance of the Controller Area Network (CAN) - the selected technology. For this task I have conducted laboratory measurements, which confirmed that the technology is reliable under the modified conditions, but on lower data transfer rate.

- Reproducing the measurements described above on trains I have validated that the prototype system based on the proposed method works reliably under the noisy environment conditions of rail transportation.
- For the automated determination of train composition and also for the proper handling of network terminations I have developed an algorithm for the case of variable topology CAN network.

Thesis III

I have developed a parameter identification method for the determination of the coefficients of the longitudinal propulsion resistance formula of the trains, which uses the track data, energy consumption, speed and position information of the telemonitoring system. The approach is model based meaning that the searched parameters are used to evaluate the energy consumption of the train, which is compared to the measured energy consumption leading to a minimization problem.

Related publications: [ABG15a]

- I have studied the state of the art of the modelling techniques of simplified longitudinal propulsion resistance and also the methodologies of determining propulsion resistance through measurement.
- I have defined the formula of the propulsion resistance, which - as a simplified model - considers the locomotive's mass and the number and mass of the rolling stock:

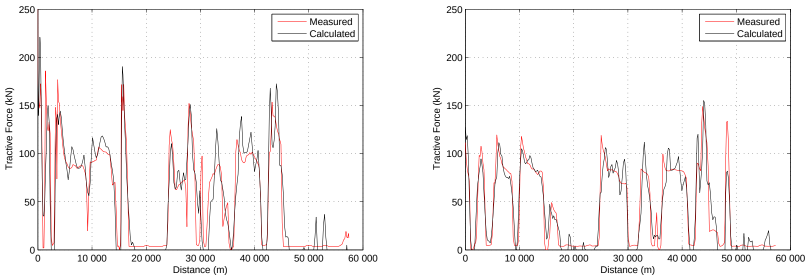
$$F_{res}^{loc}(v) = m_{loc} * (\alpha_l + \beta_l v) + \gamma_l v^2 \quad (3)$$

$$F_{res}^{stock}(v) = m_{stock} * (\alpha_s + \beta_s v) + n_{stock} * \gamma_s v^2 \quad (4)$$

- I have used the resistance formula for elaborating the energy consumption model of the train.
- The minimization of the difference between the measured and calculated energy consumption leads to the determination of the searched parameters:

$$\begin{aligned} &\underset{x}{\text{minimize}} && f(x) \\ &\text{with respect to} && x = [\alpha_l, \beta_l, \gamma_l, \alpha_s, \beta_s, \gamma_s, \xi_j, \psi_j]; j = 1, \ldots, k \\ &\text{subject to} && 0.9 \leq \xi_j \leq 1.1 \\ &&& 0.0 \leq \psi_j \leq 1.0 \\ &&& x_i \geq 0.0; i = 1, \ldots, 6 \end{aligned} \quad (5)$$

- The developed methodology was tested on actual measurements (Figure 3), by using the data of the electric locomotive series 431 of the Hungarian State Railways.



(a) Train 1 (b) Train 2

Figure 3: Measured and calculatied traction forces

Thesis IV

I have designed a method for the determination of the energy-optimal speed profile for trains. The proposed algorithm considers the parameters of the train, the speed limits of the given section and the inclinations of the track to generate a time-keeping yet energy efficient speed trajectory between two stations.

Related publications: [ABG13b],[ABG14]

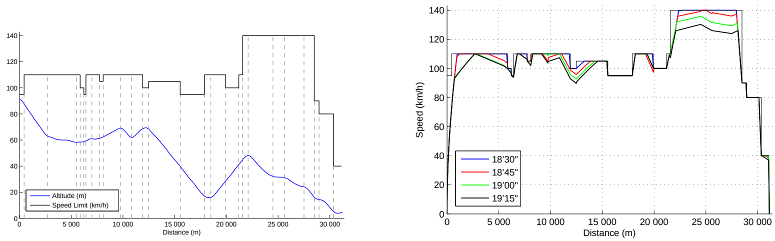
- I have shown the effects of the inclinations of the track on the energy consumption of the railway operation, and explicitly defined a mathematical formula of the time and energy consumption of driving strategies for different special conditions.

- By using these formulas and by dividing the inspected section into subsections with constant speed limits and approximately constant track gradients, the speed profile can be determined as a function of the required journey time.

- Hence, the optimal speed profile can be generated as a function of the journey time vector of the subsections. The weighted average of the cumulated running time and energy consumption could provide a possible objective function for the determination of this vector.

$$J(t_i) = W_e \frac{E(t_i)}{E^{max}(t_i)} + W_t \frac{\left|T^{calc}(t_i) - \mathcal{T}\right|}{\mathcal{T}} \tag{6}$$

- I have validated the functionality and performance of the algorithm by using the inclination and speed limit parameters of a real railway section (Figure 4).



(a) Speed limits and inclinations (b) Speed profiles

Figure 4: Speed limits and inclinations of a real railway section and the calculated speed profiles for different journey times

Thesis V

I have designed a driver advisory algorithm, which - based on a previously calculated or recorded reference run - is able to provide information about the optimal speed choice ensuring minimal energy consumption while keeping the journey time and the speed limits. The method determines the traction force requirements based on the reference run and the current state of the train.

Related publications: [ABG13b],[BAT+13],[ABG14]

- The model uses a predictive approach with the space-discretization of the section considered in the prediction, defining a speed value for each step considering the speed limits and other restrictions.
- Train driving is modelled as a control loop that consists of the measurement of the train's state, the optimum search at the prediction interval and actuation (Figure 5).

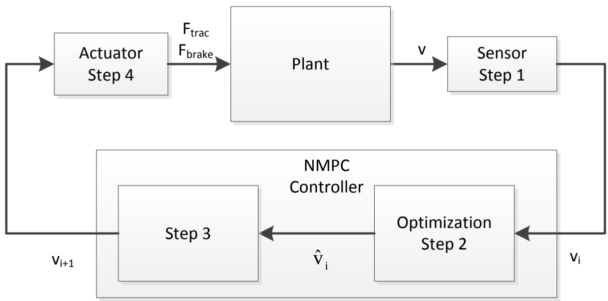


Figure 5: The control loop

- The keeping of the journey time is ensured by considering the speed (v_n) of the reference run at the end of the prediction horizon as a terminal constraint and also by minimizing the delay calculated at the same position.

3 Practical Aspects

Vehicle-to-Infrastructure networks and vehicle telemonitoring systems have been spreading rapidly in recent years. The functionalities of the existing systems are expanding, which results in the growth of the data volume generated by these applications. The field of rail traffic is not an exception to this trend. The handling of this data volume is simultaneously a problem and an opportunity. An other possible direction of development is the automated train operation, which is a known technology in some areas of fixed track applications such as subways. The data gained from the telemonitoring system can be used for extending these functionalities with the aspects of energy efficiency. Moreover this optimization may be raised to line and network level.

The problems generalized above require many low-level solutions and my research is aimed at finding the solutions to some of them, keeping in mind practical applicability.

The achievements of Thesis 1 can be utilized at the design of railway telemonitoring systems that receive and process data generated on the on-board units of a train and which also interact with them.

The functionalities of the telemonitoring system can be extended by developing an "intra-train" network on trains which do not have a dedicated communication line for miscellaneous data. Some answers to this problem are given by Thesis 2.

With the help of the algorithm outlined in Thesis 3, based on the data of the telemonitoring system, the parameters of the longitudinal resistance force equations can be evaluated without conducting special measurements. These results can be used in energy-optimization algorithms and also in other calculations of railway dynamics.

Thesis 4 provides an algorithm for determining the energy efficient speed profile of a train considering track inclinations and speed limits.This will give a reference to the algorithm designed in the next thesis and can also be used for the evaluation and training of engine drivers.

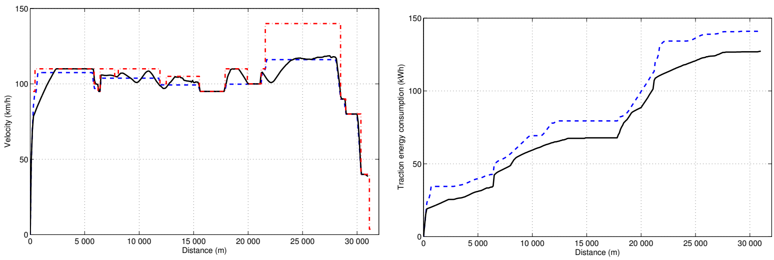
Last, the algorithm given in Thesis 5 can be a basis of an on-board advisory system that helps the train driver to keep the journey time and save energy simultaneously by providing real-time information and recommendations. Also this algorithm can be a basis for automated and energy-efficient train operation.

4 Future research

Besides the discussion of the questions of designing and operating telemonitoring system in the field of transportation, the dissertation points out that the possibilities of such systems make them much more than a simple data transfer and storage application, but rather with the appropriate processing of data they could become the fundamental tool for the optimized operation of the network in the hands of operators.

Vehicle trajectories and speed can be optimized by using the tools of numeric optimization and control theory with the result of a significant gain in energy consumption and environmental impact. This can be particularly true in the case of railways, where – due to the large mass of trains – substantial energy savings can be achieved with relatively low investments and operating costs of telematics.

I have developed an algorithm for a locomotive on-board driver advisory system that is capable of calculating a combined energy-optimal and journey time keeping speed profile (Fig. 6) between two stations based on the data provided by the telemonitoring system. Based on these achievements, recommendations can be given to the train driver to adjust optimal speed or for the direct handling of actuators. Further research should mainly focus on this problem group.



(a) Proposed speed profile (b) Cumulative energy consumption

Figure 6: Example of energy saving

Although it is not linked closely to the optimization theoretic approaches of the dissertation, one possible research direction should be the presentation of the recommendations (e.g. recommended speed or recommended engine control states) towards the train driver, which needs to consider human factors and must meet the requirements of accurate, efficient but most importantly safe transportation. One of the main questions concerning the different driver advisory systems is the adequate visualization and timing of the information provided to the driver, such as the contents of the display, the rate of updating, ergonomics, and the ease of understanding data. All these aspects not only affect efficiency but also traffic safety and therefore their research is an important task.

Another research direction could be the extension of the optimization to railway line or even network level by using the recent achievements of the field of transportation control. The algorithms presented in the dissertation focus on the control of a single train, where the traffic conditions are only considered as external conditions. The next step could be the optimal control of a railway line, since the telematics system is capable of providing the position and speed of all trains in almost real-time. Hence, the optimization could take into account the following, followed or crossing trains and the number of unnecessary brakings can be further reduced. Next research should be conducted for the optimization of the rail network of whole regions or even countries. However in the field of road traffic modelling this is the level of macroscopic approaches, in the field of railways, the relatively low number of trains enables the handling of this problem on a train level, or with some mesoscopic approach.

As can be seen from the above mentioned examples, the field of researching optimal control strategies of railway operations holds great opportunities which - in line with the current efforts of the developed countries - may facilitate the reduction of energy consumption and therefore the CO_2 emission of transportation.

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