STATE OF THE ART CONTROL METHODS FOR ENERGY EFFICIENT TRAIN OPERATION IN A RAILWAY TRAFFIC SYSTEM

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Summary
In this paper state of the art control methods for optimization of energy consumption during train traction are presented. After the train model is described the optimal control problem for energy efficient train operation is defined and a survey of solving methods is given. In the end a short review of industrial applications is written.

1. INTRODUCTION

Railway transport systems are considered as large energy consumers that accounted for 2% of overall energy consumption and for 7 million tons of CO₂ emission in Europe in 2012 [1]. For the same year in Croatia, 164.5 GWh of electrical energy were spent on transporting around 27 million passengers and 11 million tons of goods through the railway system [2]. Due to rising energy prices and environmental concerns, energy efficiency of transportation systems is becoming increasingly important and railway operators are motivated to reduce their energy consumption. One way of reducing the railway system energy consumption is through minimization of the on-route energy consumption of each individual train while respecting the time-tables, on route restrictions and passengers comfort.

This paper is structured as follows. In Section 2 continuous-time train model and optimal train control problem are defined. In Section 3 different methods of solving the control problem are presented. Industrial implementations of optimal train control systems are summarized in Section 4.

2. TRAIN MODEL AND OPTIMAL CONTROL PROBLEM DEFINITION

2.1. Train model

In the optimal train control literature, two approaches are used to describe the train model: the single mass-point and the distributed mass approach. Most commonly used is the mass point model [3], for which the motion of the train is described with a continuous-time model [4]:

\[ m \rho \frac{dv}{dt} = F_t(t) - F_b(t) - R(v,s), \]  
\[ \frac{ds}{dt} = v, \]

where \( m \) is the train mass, \( \rho \) the rotating mass factor which accounts for the rotational energy of the trains rotating parts, \( v \) the train velocity, \( s \) the traversed path of the train, \( F_t \) the train traction force, \( F_b \) the train braking force and \( R \) the overall resistance force.

Train traction force \( F_t \) is bounded by the maximum traction force \( F_{t,\text{max}} \) which is a function of velocity \( v \). At low speeds maximum traction force is bounded by the adhesion limit. Adhesion is defined as the ratio of the longitudinal force actually applied at the wheel-rail contact to the vertical reaction force, and is considered equal to the coefficient of friction between wheel and rail at its limiting value [5]. At higher speeds traction force is bounded by the characteristics of the power train (maximum tractive power, maximum train speed).

Modern railway vehicles brake systems consist of two main subsystems: an electric (regenerative) brake and a frictional (pneumatic) brake. Braking force \( F_b \) is often considered as an integrated braking curve of both braking subsystems as they are used together in a blended electro-pneumatic brake system [6]. When the regenerative braking force is not sufficient the frictional brake is applied.

The overall resistance force \( R \) comprises of: basic resistance \( R_b(v) \) including roll resistance (friction) and aerodynamic resistance, and of line resistance \( R_l(v,s) \) caused by track grade, curves and
tunnels [7]. The basic resistance $R_0(v)$ can be described according to the Strahl formula [8]:

$$R_0(v) = a_1 + a_2v + a_3v^2,$$

(2)

where $a_1$, $a_2$ and $a_3$ are coefficients determined from the actual train shape, power train and wind speed, which can be calculated from available train data. Line resistance $R_l$ calculation is more complicated but can be described by [9]:

$$R_l(v, s) = mg \sin(\alpha(s)) + f_c(r(s)) + f_r(v, l(s)),$$

(3)

where $g$ is the gravitational constant, $\alpha(s)$ the slope, $r(s)$ the curve radius, and $l(s)$ the tunnel length along the track. First term accounts for the track grade resistance, curve resistance $f_c$ is a consequence of the rigid connection between the wheels and the axle and the centrifugal force while the tunnel resistance $f_r$ is a consequence of higher air resistance in the tunnels.

2.2. Optimal control problem

The problem of energy efficient train control can be formulated as one of the problems of optimal control theory [4]. Control variable is the traction force $F$ (positive for traction and negative for braking) which can be calculated to satisfy conditions and restrictions on the control variable and the state variables (train position $s$ and train velocity $v$). In energy efficient operation of rail vehicles the objective function is the energy consumption for a required travel time, but can also be set as minimum time, total operation cost or as weighted sum of energy consumption and riding comfort.

The optimal control problem is then stated as follows [10]. At the current time denoted with $t = 0$ and characterized with a known train velocity $v_{start}$ and train position on the rail track $s(0)$, find the optimal train traction and breaking force profile which minimizes train energy consumption, while reaching the next station at time $t = T$, and respecting all given constraints on $v$, $s$ and $F$ along the rail path:

$$\min_F \int_0^T E(t)v(t)dt,$$

(4)

subject to train dynamics described in (1a) and (1b), following constraints:

$$F_{min} \leq F(t) \leq F_{max},$$

(5)

$$0 \leq v(t) \leq V_{max}(s),$$

(6)

and boundary conditions:

$$s(0) = s_{start}, \quad v(0) = v_{start},$$

(7)

$$s(T) = s_{end}, \quad v(T) = v_{end}.$$

(8)

where $V_{max}(s)$ is the maximum allowable velocity (depends on the train characteristics and the current track section limitations), $s_{start}$ and $v_{start}$ are train position and train velocity at the start of the route and $s_{end}$ and $v_{end}$ are train position and train velocity at the end of the route. The duration of the trip $T$ between $s_{start}$ and $s_{end}$ is usually provided by the railway system operator through timetables.

Additional constraints on acceleration and deceleration may be added in order to ensure the passengers comfort. Riding comfort can also be considered by adding a term in the objective function which is expressed as a function of the change of the control variable $F$.

In the following section, different approaches to solving the optimal train control problem are presented.

3. OPTIMAL CONTROL METHODS

During the early research on the optimal train control problem, solution to the optimization problem was obtained using different simplifications such as linearization of the controlled object and constant constraints on control variables [11], [12]. The resulting optimal control sequence consisted of four different sections: (i) maximum acceleration, (ii) cruising at constant speed, (iii) coasting (zero traction force) and (iv) maximum deceleration [13].

Further research methods can be separated in: (i) analytical solution methods and (ii) numerical optimization methods [7], [14]. Analytical methods hardly cope with adding more realistic conditions and complex nonlinear terms in model equations and constraints. In numerical optimization approaches, the optimal solution is not always guaranteed since the obtained solution could be a local minimum and the computation time is often too long for real-time applications [7].

Analytical solution methods can be further divided depending on the continuity of the train traction and braking force [15]. Freight diesel locomotive is the only railroad equipment which still uses discrete traction force control while modern traction systems may produce any traction force within power and adhesion restrictions [4].

Research on the discrete traction force model was done by the Scheduling and Control Group (SCG) at the University of South Australia, based on a typical diesel-electric locomotive in which the driving control is a throttle setting that determines the rate of fuel supply [16]-[20].

Under the assumption of continuous traction force, in the 1980s Golovitcher found a solution which includes varying slopes (including steep climbs and descents) as well as speed restrictions and variable restrictions on traction and braking forces. These results were later extended to include
electrical locomotives with regenerative braking. Based on the former research during the 1980s a complete solution of the optimal train control problem was given by Liu and Golovitcher [4]. In [15] Howlett applied the Pontryagin’s principle to find necessary conditions for the control problem. New approaches have been developed by Howlett, Pudney and Vu [21] who showed that the global optimal control strategy can be obtained by applying a local energy minimization principle over each steep section.

Another aspect of choosing the controlled object model is consideration of efficiency of the traction power system. In above studies, the train traction efficiency is assumed constant while in real operation it varies with train speed, track slope and other operating conditions. Detailed train model including the propulsion system efficiency and regenerative breaking was considered by Franke [14], who showed that no maximum acceleration or maximum deceleration is applied at high velocities because of large power losses.

Numerical optimization methods like dynamic programming require long calculation times to find the solution and therefore might not be feasible to solve the optimal train control problem on an on-board computer for real-time calculations [4]. Some researchers proposed a pre-computed optimal control law in a form of look-up tables that are selected in the railway operator management centre based on the currently estimated train mass and required time to reach the destination station [10], thus ensuring that there is enough time to compute the optimal control law. Due to computer technology development, available computing power has significantly increased and more researchers are developing numerical optimization methods for the optimal train control problem.

Techniques such as fuzzy and genetic algorithms have been researched to calculate the optimal train control law. Different researchers proposed fuzzy automatic train controllers or evolution algorithms to optimally tune the fuzzy membership functions [22]. Genetic algorithms were implemented by Chang and Sim [23] and Han et al. [24]. Other methods such as combinations of neural networks and genetic algorithms, genetic algorithms and fuzzy logic, were also proposed in literature.

Dynamic programming was proposed by Franke [14], where a more detailed nonlinear train model with power loss of the locomotive inverter was used. It was concluded in [14] that discrete dynamic programming copes better with nonlinear optimal control problem compared to sequential quadratic programming because of the deterministic calculation time and the result obtained in the form of a feedback control law. Dynamic programming, gradient method and sequential quadratic programming were also introduced to optimal train control problem solving in [25]. In [10] multi-parametric quadratic programming was used to calculate the optimal train control law resulting in a time-varying piecewise affine function, which relates the traction force to the train position and speed. Therefore, this is an off-line computed optimal feedback control policy that can be easily evaluated on-line.

4. INDUSTRIAL APPLICATIONS

The development of computer technology and embedded systems gave the foundations for many companies to develop train control and automatic operation systems known as automatic train operation (ATO) or positive train control (PTC) both implemented worldwide and mainly focused on safe train operation. In an ATO system, the high-level control is responsible for calculating the optimal speed-position reference trajectory based on the collected train information [7].

In order to ensure energy-efficient train operation, driver advisory systems (DAS) were integrated, such as the GSM-R Driver Advisory System from the German well known company Siemens or the EBI Drive 50 Driver Assistance System from the Canadian company Bombardier. French company Alstom is also known for implementing DAS in their ERTMS systems.

One of the most recognized DAS systems is the Energymiser system developed by the TTG Transportation Technology, which has been installed on passenger and freight trains worldwide showing energy reductions from 10-20%.

Among other DAS systems, GreenSpeed Driver Advisory system from Cubris, Leader Driver Advisory System from Knorr-Bremse as well as Toshiba’s Energy Efficient Train Traffic Control system are worth mentioning.

5. CONCLUSION

As presented in this paper, control methods for energy efficient train operation have been well researched in the optimal control research community. Various analytical and numerical approaches were introduced towards finding the solution of the optimal train control problem ranging from Pontryagin’s maximum principle to dynamic programming and genetic algorithms.

Analytical approaches meet difficulties when more realistic conditions are introduced while numerical approaches often result in too slow computation and the solution found is sometimes not optimal. Therefore a trade-off between accuracy and computational efficiency is proposed by many researchers.
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7. REFERENCES
