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Chapter 8
Energy-Efficient Train Operation: Conclusions and Future Work

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8.1 Conclusions

The increasing mobility, congestion and environmental impact of transport is a major concern to societies worldwide. The railways offer a sustainable mode of transport to face these societal challenges and are facing a significant growth in demand. Railway transport is the most energy-efficient means of transport due to the low friction of the steel wheel-rail interface, and specifically electric trains—representing 75% of the passenger-kilometres by rail worldwide [2]—are a sustainable means of transport, both in terms of energy efficiency and greenhouse gas emissions. The increasing railway transport demand and saturating railway capacity motivate further research and deployment of energy-efficient train operation. Train headways are getting much shorter by modern signalling and control technology, as well as planning for optimal usage of infrastructure to accommodate the growing train frequencies. This gives additional challenges to maintain stable railway traffic without unnecessary braking and re-accelerating, while also opportunities arise to re-use regenerative braking energy by nearby trains.

Train drivers can use a variety of driving strategies to operate a train from stop to stop and as such use the available running time supplements in different ways. Energy-efficient train operation makes use of optimal cruising speeds (speed holding)

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and coasting (no traction) to save energy, whilst accelerating as fast as possible to reach the optimal cruising or coasting speed, and braking as fast as possible before speed restrictions and stops. The optimal sequence and switching points between these four energy-efficient driving regimes—maximum acceleration, cruising by partial traction, coasting, maximum braking—depend on the available running time supplement, the rolling stock characteristics, and the track characteristics such as gradients, curves, tunnels and speed limits that may vary along a route. For short distances, the cruising regime may be absent when the optimal cruising speed cannot be reached before coasting already has to start. When regenerative braking can be applied another cruising regime by partial regenerative braking on declines can also be used. On steep inclines (where maximum tractive effort is not sufficient to maintain speed) and steep declines (where speed increases while coasting), the optimal switching point to respectively maximum acceleration and coasting is earlier than the incline/decline and it also lasts longer before switching back to cruising after the slope.

The optimal train trajectories can be derived using optimal control theory, and in particular by application of Pontryagin's Maximum Principle. The resulting train trajectories can be visualized in time-distance and speed-distance diagrams, and likewise the associated optimal control and energy consumption can be visualized in diagrams as function of distance or time. The main difficulty in the train trajectory optimization problems is the determination of the switching points between driving regimes, which can be many depending on the track characteristics, especially the gradient profile and speed limit profile.

Energy-efficient train trajectories should be incorporated in the railway timetabling process. Traditionally, timetable planning is based on calculations of the technical minimum running time between two stops to which a running time supplement is added as a fixed percentage or an absolute number, after which the result is rounded up to the required precision (mostly minutes). As a next step, the optimal train trajectory can be computed for the given fixed scheduled running time. This train trajectory gives the optimal drivable time-distance train path that can be used to derive target passage times at critical intermediate timing points, as well as the optimal cruising speed and coasting points for punctual driving. This detailed timetable information can be provided to the drivers to assist in energy-efficient driving as opposed to merely providing the scheduled departure and arrival times at the stops. In particular, this gives essential timing information for possible intermediate short stops and passage times at railway junctions, as well as speed advice for speed restrictions and before steep slopes such as tunnels and bridges.

Any track occupation conflict should be solved in a conflict-free timetable as a basis for energy-efficient train operation that avoids unnecessary braking and re-acceleration due to route conflicts. Therefore, microscopic railway timetabling based on blocking time theory is replacing traditional normative macroscopic timetabling in order to optimally allocate train paths to scarce and saturated railway infrastructure. The blocking time theory guarantees that signalling constraints are incorporated correctly in the timetable design. The microscopic infrastructure occupation associated to a train trajectory can be derived in terms of blocking times, which is used for conflict detection between train paths by which conflict-free timetables can be obtained. Train trajectory optimization algorithms should be used as the main running time calculation method, such that the resulting timetables and infrastructure occupation are based on energy-efficient train speed profiles. This will guarantee a perfect alignment with the actual train operation, in particular when supported by Driver Advisory Systems (DAS) or Automatic Train Operation (ATO).

Regenerative braking energy may contribute to the total energy consumption. The related strategies include synchronization of arrivals and departures in the train timetable, coordinated train control between braking and accelerating trains, and the application of energy storage systems, which should all be considered to realize the optimal usage of regenerative energy. In particular, coordinated control between regenerative braking trains and nearby accelerating trains with reused regenerative energy via the power supply network has potential for energy savings. Information of train operation and the active power substation can be shared to generate a more comprehensive energy management strategy in real-time such that the total energy consumption is minimized. Hence, this requires an integrated systems approach between train operation and power supply system.

On-board and track-side energy storage systems can be implemented in the railway systems to improve the utilisation of the surplus regenerative braking energy and reduce traction power demand. The original energy-efficient train driving strategies are no longer the optimal strategies for railway systems with energy storage devices. New objective functions considering energy storage models are proposed for the optimization. Some case studies based on the Metro in Madrid have been developed considering various operation and infrastructure scenarios. Track-side energy storage systems reduced energy consumption by 9.72–10.19% in scenarios with low-density traffic. However, the energy reduction ratio decreased to 1.8–2.07% in scenarios with high-density traffic. On the other hand, installing on-board energy storage systems could be beneficial in low-traffic lines with low receptivity to regenerated energy, where savings between 7.46% and 11.67% have been obtained. However, their application in dense traffic conditions or with high network receptivity would increase energy consumption because of the increase in train mass.

Electric trains are supplied with energy by the traction power supply network. Multiple trains are moving along the power supply network requiring traction power demand when accelerating and feeding back the regenerative braking power when decelerating. Modelling of the multi-train traction power supply network plays a significant role in evaluating railway system energy flow and validating the energy-efficient train operations. Both DC and AC traction power supply networks with various voltage levels are widely used across the world. The equivalent circuits of substations, transmission network and trains can be derived by mathematical equations. The power flow through the traction power supply network and multiple trains can be solved by piecewise iterative power flow analysis algorithms. The train speed trajectory and timetabling models provide the real-time train power demand and location, which can be fed into the power network simulation to calculate the detailed energy flow including the substation energy consumption, transmission losses, and regenerative braking energy utilisation. The multi-train power network simulation can be used to validate, evaluate and optimize the energy-efficient train operation strategies.

8.2 Future Work

Timetables are the basis for the real-time traffic plan that a railway traffic management system maintains to match the real-time route setting to the train paths [6]. The real-time traffic plan contains the allocation of successive track sections and blocks to train paths. In particular, in a digitalized railway system the real-time traffic plan can be used by DAS and ATO trackside systems to compute train path envelopes (or journey profiles) that are sent to the DAS/ATO onboard systems [9]. These train path envelopes define the target times or time windows at timing points along the route of a train that can be used as constraints by an onboard train trajectory optimization algorithm to compute the energy-efficient train trajectory given the actual rolling stock parameters and conditions, while avoiding conflicts with other train trajectories. In practice, the parameter values and conditions may differ from the ones assumed during timetabling, and therefore the actual train trajectories may also deviate more or less from the planned ones. For instance, in a periodic railway timetable the scheduled running times will be the same for all trains associated to a given train line that run with a given frequency over the day. However, the train compositions may vary over the day with different train lengths corresponding to the fluctuating transport demand over different periods of the day. Hence, these train compositions vary in length, mass, resistance and traction characteristics, and therefore the individual optimal train trajectories may also vary slightly. In addition, a traffic management system monitors train delays and adjusts the timetable in case of disturbances to maintain a conflict-free traffic plan using conflict detection and resolution algorithms. The updated real-time traffic plan will then provide new targets to the trains via updated train path envelopes. Then the task of the driver or the DAS/ATO onboard systems is to generate and track train trajectories within the provided train path envelopes, such that the trains operate energy efficiently in green waves over the network. The interaction between the traffic management systems, DAS/ATO trackside and DAS/ATO onboard systems, as well as the signalling systems for mainline railways is an active research area.

A recent research area is cooperative train control of a convoy of trains that move synchronously as close as possible. Train separation by more than the absolute braking distance has always been a safety principle in railways to avoid collisions in the case a train might derail. A major paradigm shift is the virtual coupling concept where successive trains use vehicle-to-vehicle communication to virtual couple and proceed as one platoon following a master train with coordinated traction and braking [7]. In this case the trains can follow at a relative braking distance while keeping a safety margin to the rear of the predecessor even when this predecessor executes emergency braking [8]. Under virtual coupling, the dynamics of the trains in a platoon will be dominated by tracking the relative distance and speed with the predecessor and the master train rather than tracking a dedicated train trajectory. This will affect the energy consumption of the platoon. The optimal joint multi-train trajectory optimization of a platoon regarding energy efficient driving of all virtually-coupled trains is still an open research topic.

In recent years, the digital twin technology (DT) has become one of the most popular research directions with high expectations. The digital twin is meant as the virtual and digital counterpart of a physical system that can be used to simulate the real system for various purposes, exploiting a real-time synchronization of the sensed data coming from the field [5]. With the vigorous development of the Internet-of-Things, high-speed communication, big data analysis, intelligent algorithms and other technologies, the digital twin technology has sufficient support from theory to technology, and is gradually applied to various fields such as industry and medicine. Different from traditional simulation, the advanced digital twin technology enables the model to have significant advantages such as real-time interaction, data-driven, and independent adjustments.

As an important part of the railway system, the traction power supply system is responsible for providing energy and power for running trains. Energy flow in the traction network is an important characteristic for the traction power supply system operation, and is the main basis for system capacity configuration and energy saving optimization. Constrained by the complexity of the system and security factors, modelling the energy flow for a traction power supply system is generally realized by traditional model simulation methods [10]. A data-driven modelling method based on the digital twin technology can be adopted to accurately simulate the energy flow for (urban) rail traction power supply systems in the future. Combined with the general architecture of a digital twin model [1], the digital twin architecture of an urban rail traction power supply system can be designed, including six major components: a physical layer, perception layer, transmission layer, data layer, computing layer and application layer. The physical layer refers to the physical object of the digital twin model, i.e., the real physical entity of the traction power supply system. Based on sensing and data acquisition technology, the perception layer collects a variety of quantities of the state representing the electrical characteristics of the physical layer, and then uploads the collected data to the data layer server at a high speed through the transmission layer. The data layer stores the original collected data to the cloud database, and processes the data. As the core part of the architecture, the computing layer improves the accuracy of the model. The computing layer mainly includes the integrated system model, correction algorithm, simulation model and the other key content. The application layer is the decision-making and design optimization application based on the model results and measured data. The decision-making optimization results are stored in the data layer and can directly act on the physical layer for decision-making guidance.

To achieve net-zero railway systems, the study of interactions of the railway network with the electrical power grid and renewable energy generation is attractive. A smart soft open point allows a controllable energy exchange between railway network and power grid to transfer the surplus power from the railway network to support the weak power grid [3]. Renewable energy and energy storage hubs can be installed along the railway network to increase the railway power supply capacity with lower grid upgrading costs and reduce the peak power demand. It also provides an opportunity in developing railway self-sufficient energy supply networks [4]. The main challenge is to control the large-scale railway and energy systems in a coordinated and smart way, which requires the development of digital and control technologies. With the advantages of the digital twin based modelling technology for the railway traction power supply system, real-time information interactive transmission is enabled between the digital model and the real-world system. The real system can be perceived in real time according to the collected state data, and meet the data requirements for the model itself. Therefore, digital twin based technology will enable the management of trains with renewable energy flow, promoting sophisticated integrated energy-saving methods of energy management and train operation.

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