

Modelling and strategies for the assessment and **Optimisation**
of **Energy Usage** aspects of rail innovation

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ABBREVIATIONS

Acronym	Description
ATO	Automatic train operation
C-DAS	Connected Driver Advisory System
CATO	Computer aided train operation
CER	Community of European Railway and Infrastructure Companies
DAS	Driver Advisory System
DMI	Driver machine interface
EETT	Energy-efficient train timetabling
EETC	Energy-efficient train control
GA	Genetic algorithms
HST	High-speed train
IM	Infrastructure manager
MPGA	Multi-Population genetic algorithm
PMP	Pontryagin's Maximum Principle
RU	Railway undertaking
SGA	Standard genetic algorithms
TPE	Train path envelope
TMS	Traffic management systems
UIC	International Union of Railways

EXECUTIVE SUMMARY

This report has been prepared as Deliverable D04.1 "DAS assessment" in the framework of the EU co-funded, specifically relating to WP4, Task 4.1 "DAS comparative assessment". The objective of this task is to summarise the main functionalities and characteristics of stand-alone DAS (S-DAS) and connected DAS (C-DAS) and their suitability for energy management and optimisation of driving strategies. More specifically, this task is a comparative assessment of S-DAS and C-DAS and their relevance to the four operation scenarios i.e. urban, regional, high speed and freight operations (OPEUS D3.1, 2017).

This report reviews and discusses the variation of optimization algorithms, driving strategies and models which are the principle and fundamental methods of deriving optimal energy-efficient driving strategy/advice. This report discusses the aspect of the energy-efficient train control (EETC) and energy-efficient train timetabling (EETT), including how different operation types influence energy optimisation.



1 INTRODUCTION

The UIC (International Union of Railways) and CER (Community of European Railway and Infrastructure Companies) have set targets to decrease energy consumption and CO₂ emissions for the railway sector by 30% over the period 1990 to 2020, by 50% in 2030. In do so, the European railways will strive towards complete carbon-free train operation by 2050. The energy consumption of railway companies should be decreased by 30% in 2030 compared to 1990 (UIC, 2012). In general, approximately 85% of total energy consumption by the rail sector is used directly (5-10% energy losses) for rail traction (UIC, 2015). 70–90% of the total energy consumption in urban rail is due to rolling stock operation, whereas the rest is used in stations and other infrastructure within the system (González-Gil et al., 2014).

Optimisation of energy consumption for railway operation systems is defined by a wide range of interdependent factors. To date, the main practices, strategies and technologies to minimise railway operation energy use include: regenerative braking, Eco/energy-efficient driving, traction losses reduction, comfort functions optimisation, energy metering, smart power management and renewable energy generation.

Optimal energy-efficient driving strategies can reduce operating costs significantly by reducing energy consumption due to the driving strategy applied and the scheduled running times in the timetable. In addition these strategies result in a smoother driving, leading to lower friction between steel wheels and rails, which translates into less maintenance costs of those elements. Optimisation of energy consumption can be achieved by EETC enabled trains driving with the least amount of traction energy, also by providing a most effective timetable which is EETT to achieve this goal. The optimisation models and efficient algorithms to compute the optimal train regimes for energy-efficient train control strategy under different conditions could be used in real-time Driver Advisory Systems (DAS) or Automatic Train Operation (ATO) systems.

1.1 Overview of DAS

Generation of energy efficient train trajectories can be modelled by solving a complex optimisation problem with nonlinear and time-varying variables under multiple constraints of equality and inequality, as train operation is a dynamically factor influenced process due to complex railway operational conditions (Zhu et al.,



2016). The Driver Advisory System (DAS) delivering optimised energy-efficient trajectory train operation advisory to the driver based on static or real-time railway operation information. This report identifies, assesses and compares the two variants operational concept of DAS which is S-DAS and C-DAS defined in RSSB (2012) and Network Rail (2015):

- Standalone DAS (S-DAS) is a driver advisory system which has all data downloaded to train at or prior to journey start. It provides train drivers an advisory train speed that is determined by the real-time measured progress of an individual train against predefined route geography and schedule data. Its primary use is to optimise energy usage.
- Connected DAS (C-DAS) is a driver advisory system with an advisory train speed (limited by the line speed profile and maximum train speed) that is determined by the real-time, dynamic update of schedule information via a telecommunications link to a control centre that is monitoring the location and speed of many trains in an area. It can be used to optimise energy, capacity or network performance. This enables a communications link to the IM control centre in each controlled area in which the train operates.

This enables the provision of schedule, routing and speed restriction updates to trains in near real time, and also receipt of information from trains to the IM control centre to improve regulation decisions. In an uncontrolled area C-DAS will operate with initial data (as per S-DAS), or with the most recent updates received from an IM control centre or RU-managed system(s).

1.2 Current development status of DAS

From the first simple models from the 1960s by Pontryagin's Maximum Principle (PMP) (Pontryagin et al., 1962) research to minimise a train operation energy consumption by optimal driving strategies has been, and still is, a hot topic.

The energy consumption of an optimal driving method designed by Genetic Algorithms (GA) (Chang and Sim, 1997; Wong and Ho, 2004) combined with Fuzzy Logic (Hee-Soo, 1998) with fuzzy parameters (GA-F) has been applied to a Spanish high speed line providing 6.7% energy savings compared with the typical manual driving style. Previous research by Sicre et al. (2012) demonstrated that energy savings of around 20% were measured on non-delayed services of the offline design eco-driving for the commercial time table on high-speed lines.



To find the optimal sequence of driving regimes and the switching points between the regimes for different operation circumstances and train types, then to deliver the optimal driving strategy into feasible and understandable advice to train drivers in real-time has led to considerable research in developing real-time DAS (Kent, 2009; ON-TIME, 2013; Panou, Tzieropoulos and Emery, 2013). Energy savings of between 20–30% have been reported when applying EETC in a DAS compared to normal train operation (Franke, Terwiesch and Meyer, 2000; ON-TIME, 2014a).

Experiences with implementation, studies and simulations with DAS using these systems can contribute significantly improvements in punctuality and energy efficiency. As UIC established (UIC Technical paper), the energy saving potential of the system level DAS and ATO solutions depends mainly upon the service type and profile (urban, suburban, regional, intercity, high speed and freight), DAS/ATO level, the available time reserves in the schedule, the actual status of energy management and energy efficiency for a given operator before the implementation. As DAS gives recommendations, the saving potential thus strongly depends on the actual usage of the installed system which is accepted by the drivers.

S-DAS products were originally developed for the long-haul freight market in the USA and Australia, and have more recently been adapted for use on passenger fleets (RSSB, 2012). A number of such products are currently operational in the UK and worldwide. C-DAS products are starting to emerge and they were first operated in countries such as UK in April 2015. Most of the C-DAS products have evolved from the S-DAS product linked to the emerging traffic management system.



2 COMPARATIVE ASSESSMENT

This section evaluates the implementation and development of the technical requirements and operational guidance of C-DAS and S-DAS, allowing for maximum flexibility in supporting their operational requirements.

2.1 Implementation benefits

The implementation of any DAS is intended to deliver benefits on energy cost savings, an associated reduction of carbon emissions and increased efficiency of train operation, and in punctuality and quality of service. The benefits from the implementation of S-DAS also provide improvements in train regulation under unperturbed conditions. The additional benefits resulting from the implementation of C-DAS are expected to improve the network capacity and train regulation under perturbed conditions.

According to Network Rail (2015), the primary benefits resulting from the implementation of S-DAS are expected to be as follows:

- a) Improved safety
- b) Improved fuel efficiency
- c) Reduced wear and tear due to reduced braking and lower running speeds
- d) Improved capture of delay attribution data

Network Rail (2015) also indicated that the expected additional benefits when DAS is operating in connected mode C-DAS is the capability to receive schedule updates and to feedback train position to traffic regulation centres providing:

- a) Improved recovery from disruption
- b) Train regulation to the revised schedule
- c) Support for regulation to optimise network capacity or performance (based on fewer delays due to red signals)
- d) Support for improved conflict resolution (based on trains' predicted running)
- e) Energy, carbon and wear and tear benefits are expected to be achieved on upwards of 90% of journeys in comparison with 75% (observed for inter-city passenger trains) of journeys with S-DAS, due to schedule revisions being available near-real time and thus usable by C-DAS for late running trains.
- f) In addition, both DAS variants may support a future anticipated capability to optimise energy consumption based on locally available electrical power supply or power tariffs/budgets.



2.2 Comparison of Characteristics between S-DAS and C-DAS

This section explores the relationship and operation characteristics between C-DAS and S-DAS.

The architecture of S-DAS implementation includes an on-board and trackside sub-system, and a means for information to be passed between these sub-systems. There is no interface to trackside or on-board signalling, or to train regulation systems. The C-DAS comprises on-train and off-train subsystems, and includes an off-train subsystem which provides an interface with the Infrastructure Manager's (IM) Traffic Management system.

The C-DAS operates in the context of a Traffic Management system which has the capability to revise the schedules and/or routing of trains in the area it controls. Therefore, C-DAS can be used to optimise any of network capacity, performance or energy. There is no dependence on trackside systems for real time data processing for S-DAS, so the S-DAS advisory information does not affect sectional running times sufficiently.

The on-train C-DAS subsystem will operate as an S-DAS if it is unable to receive updates from the off-train subsystem.

Responsibility for the following lies outside the scope of the C-DAS:

- Calculating revised train schedules
- Monitoring train locations (other than self-monitoring by the on-train C-DAS subsystem)
- Route setting
- Monitoring signalling states

An example of S-DAS and C-DAS system architecture from RSSB (2012) and Network Rail (2015) are provided below, in Figures 1 and 2 respectively:



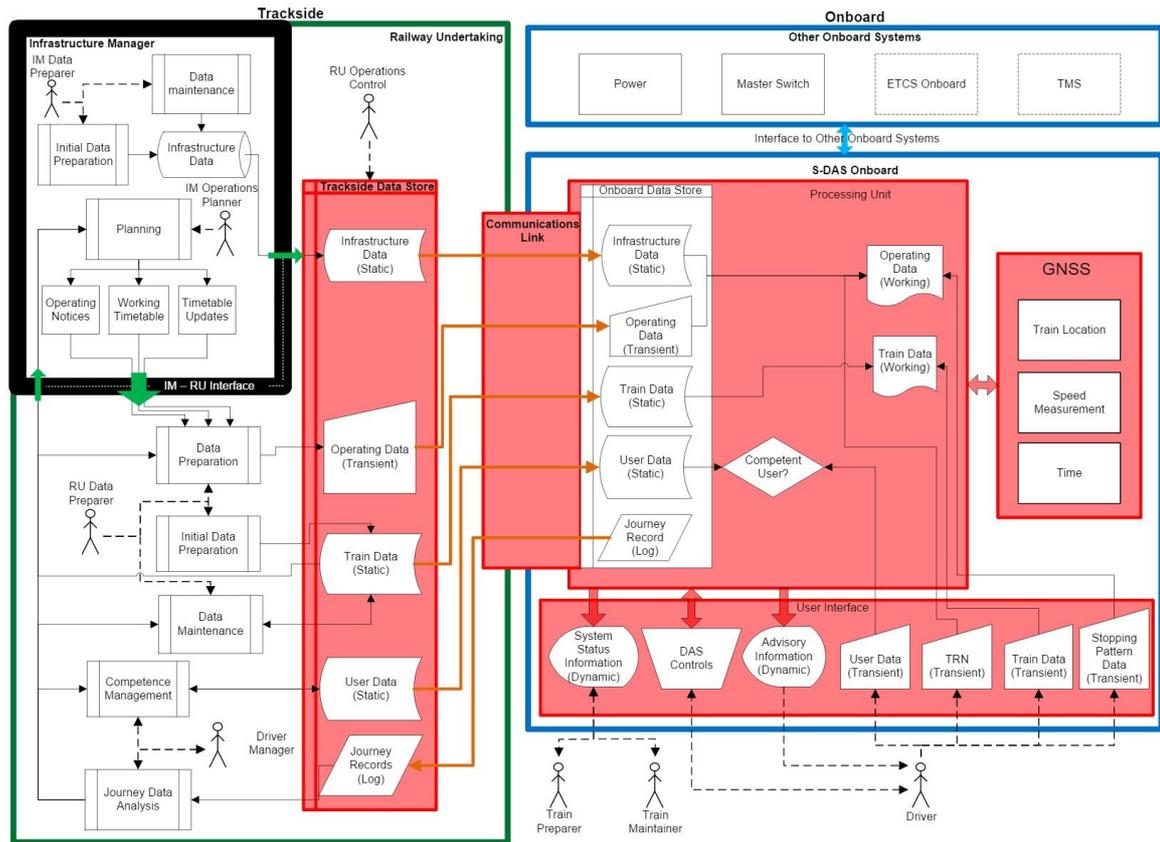


Figure 1: Example of S-DAS System Architecture (RSSB, 2012)

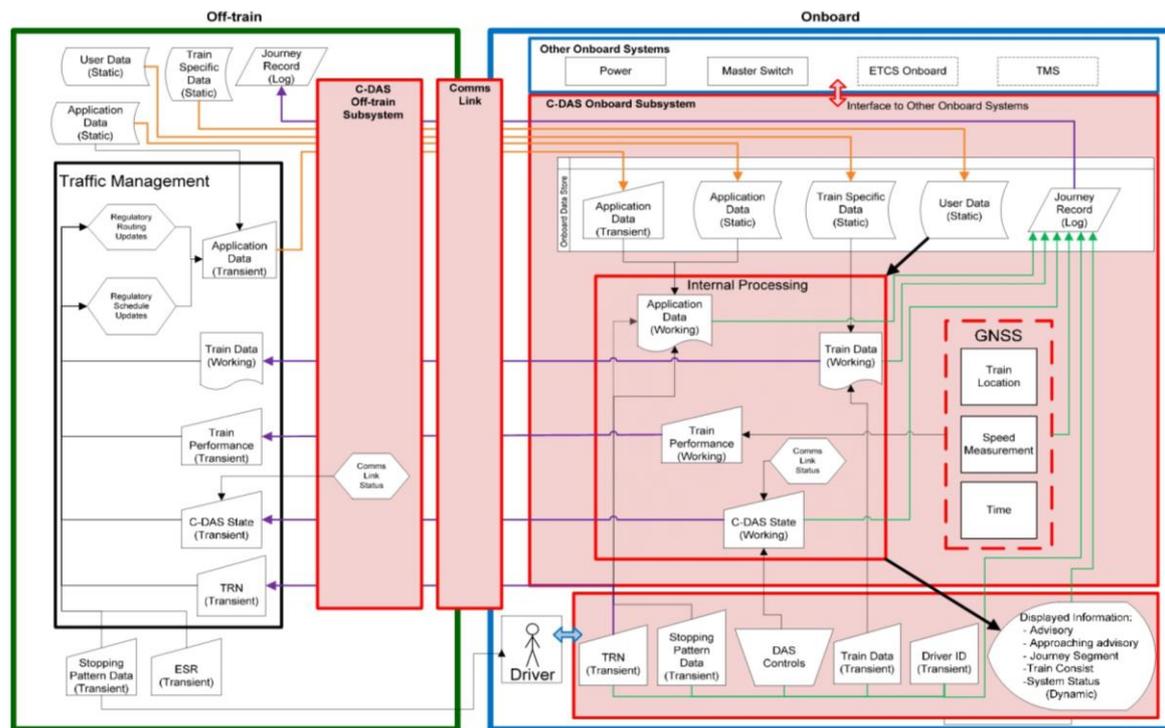


Figure 2: Example of C-DAS System Architecture (Network Rail, 2015)

2.2.1 On-train subsystem

The Driver Machine Interface (DMI) design principles and functionality for S-DAS and C-DAS are the same, as it reflects feedback from practical experience of using DAS in operational service. C-DAS requires a small number of further controls and indications.

C-DAS must have the capability to provide driver advisory information in both controlled and uncontrolled areas. In a controlled area, C-DAS fitted trains operating in a controlled area, must be capable of receiving updated application data. At the same time, they must be capable of providing train movement information to the Traffic Management System that will facilitate accurate prediction of future movements of C-DAS fitted trains.

Information provided to drivers by both S-DAS and C-DAS are wholly advisory. The status of the advice must be clearly defined and communicated to drivers. Both the S-DAS and the C-DAS must not impact negatively on safety.

- Comparing the system method, the S-DAS must only present advice to the driver when it is beneficial to follow the advice. C-DAS should only display information that is useful to the driver and has the potential to enhance his/her driving technique.
- Following the S-DAS advisory information must not lead to drivers having to brake excessively on the approach to station stops or for speed decreases. C-DAS must not advise drivers on when to brake.
- Advisory speed and distance information must be displayed in the same units employed by the in-cab speed display for both S-DAS and C-DAS. In addition the distance information must be displayed in the same units employed by other in-cab distance information by the C-DAS. Also, switching between speed and distance units must be performed automatically.

Some operation principles only apply to C-DAS:

- a) The C-DAS system should preferably not require a driver to re-enter any data that has already been input to another on-train system.
- b) Driver operation with DAS should as far as possible be the same in controlled and uncontrolled areas.
- c) Drivers must not be required to acknowledge receipt of data updates or changes to advisory information.



- d) Absence of a working or fully functioning C-DAS must not be taken as a reason to take a train out of service, or to delay it whilst repairs are carried out. Trains may enter service from a depot without a working or fully functioning C-DAS.

In comparing the S-DAS and C-DAS Energy Efficient Speed Profile Calculation, both S-DAS and C-DAS must be taken of the particular type of route, service pattern, traffic type and driving policy when configuring the processing algorithms. The data processing algorithms must be capable of being configured to meet changing operational requirements.

The S-DAS system has the same function as C-DAS on-board subsystem, it must calculate and provide accurate advisory information for the specific train so that it supports the driver in meeting the current schedule in an energy efficient manner.

C-DAS supports the driver in meeting the current or updated schedule/time table data and partial and/or segmented updates to route geography data and specific network models in an energy efficient manner.

The advisory information presented to the driver should be calculated so that it:

- a) Limits the maximum speed;
- b) Minimises braking;
- c) Uses the traction system (including regenerative braking) in its most efficient power setting.

The energy efficient speed profile must take the following into account:

- a) Scheduled departure and arrival times at timing points and station stops;
- b) Actual train characteristics, for example traction and braking profiles, rolling resistance, weight, length and maximum train speed;
- c) Temporary speed restrictions (TSR);
- d) Route geography.



2.2.2 Off-train subsystem

The off-train C-DAS subsystem provides an interface between the Traffic Management system and the trains which it manages:

- Management of telecommunications links between ground and trains;
- Management of data transfers between Traffic Management and trains, to include message construction and deconstruction, and routing;
- Mediating updates to schedule and route geography data between Traffic Management system and on-train C-DAS;
- C-DAS fault handling.

The route geography and timetable data are supplied by the IM for S-DAS. For C-DAS this data will be provided from the IM's Traffic Management system via an interface still to be defined. The off-train C-DAS will then process this data for transmission to the on-train C-DAS subsystem. The processing will be constrained by the interfaces with the Traffic Management system and with the on-train C-DAS subsystem shown in Figure 3.

For both S-DAS and C-DAS, on-train GPS-based devices are needed to monitor location and speed against the profile recommended by the DAS. However, C-DAS requires a better device to provide train location so as to operate in obstructed environments and to discriminate between adjacent tracks.



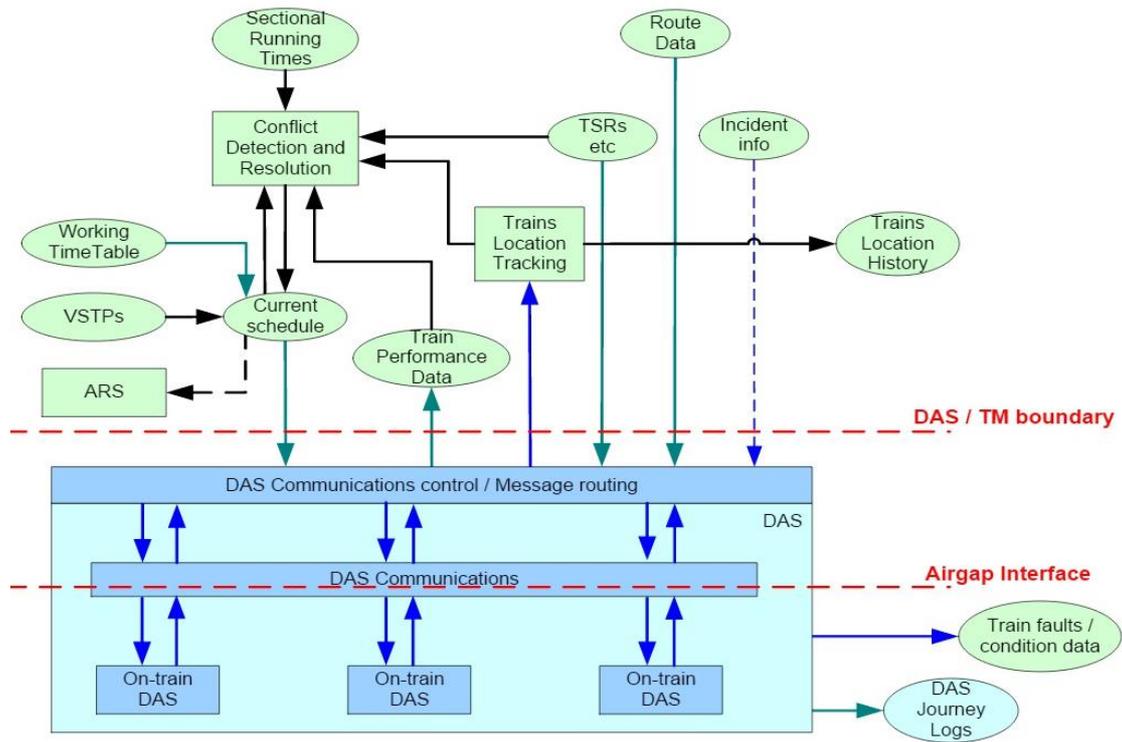


Figure 3: C-DAS and its interfaces (RSSB, 2012)

3 ENERGY MANAGEMENT

3.1 DAS influence on energy optimisation

Average saving potentials on system level are between 5% and 10% for standard DAS/ATO solutions (level 1) without connection to Traffic Management Systems (TMS), between 8% and 12% for connected DAS/ATO (C-DAS, C-ATO, =level 2) and >10% for level 3 solutions which manage conflicts and harmonize traffic flow on system level and even allow for the integration of energy efficiency into the building of system-wide train schedules (UIC), as shown in Table 1:

Energy optimisation level	Average saving potentials	System
level 1	5% and 10%	without connection to TMS
level 2	between 8% and 12%	connected to DAS/ATO
level 3	>10%	Integration of system-wide

Table 1: Energy optimisation level

Lehnert and Ricci (2018) also point out that the DAS operating at level 1 are widely available on the market. The use of DAS at levels 2 or 3 would provide potential savings around 5% additionally at diesel traction and could potentially be higher at electrical traction from the existing implementations results of DAS. The actual values of saving potentials highly depend on the concrete conditions for a given line. The higher values of the respective ranges tend to refer to suburban and regional services with stop & go regime and short distances between stations, whereas the lower values tend to represent intercity and high-speed services.

With increasing level of DAS solutions, the systems become more complex, and a growing number of systemic aspects has to be taken into account for successful implementation. Since the implementation rate in the European Railway Sector is only 1-3%, the remaining potential market still to be exploited is very high. The implementations in the next few years will be DAS solutions mostly and with a small share of C-DAS solutions (UIC).

To achieve energy optimal for train operation, reduce the traction energy of train. This can be applied with the eco-driving EETC system and by scheduling more effective timetable in EETT. In general, the optimal sequence and switching points

of the optimal driving regimes are not trivial. Therefore a range of optimisation models and algorithms to compute the optimal train trajectories and optimise timetables with a trade-off between energy efficiency and travel times to derive optimal energy-efficient driving strategy depends on different trains under different conditions. This section focuses the on discussion on the EETC and EETT in the four operation types: urban, regional, high speed and freight.

3.2 Energy-efficient train control

For different transport modes, there is a significant variability of energy dissipation patterns between different systems (urban, regional, freight, high speed). Therefore, the implementation of energy saving strategies are required specifically for each individual systems. This section discusses the characteristics of the different systems and the implementation of energy saving strategy, especially the DAS.

Urban

The first study on energy-efficient train control was carried out by Ichikawa (1968) for the urban train in Japan. He conducted the analysis of four driving regimes on level tracks to derive the optimal control rules by analytical expressions of applying the PMP to various regimes. Following this, Strobel et al., (1974) continued the Ichikawa (1968) research for the optimal control strategy, and modelled the resistance force as a quadratic function of speed with an additional term for gradient resistance. Thus finding one more driving regime for varying gradients:

1. Maximum acceleration (MA) (Ichikawa, 1968)
2. Cruising by partial traction force (CR) (Ichikawa, 1968)
3. Coasting (CO) (Ichikawa, 1968)
4. Cruising by partial braking (CR2) (Strobel, Horn and Kosemund, 1974)
- 4/5. Maximum braking (MB) (Ichikawa, 1968)

Strobel et al., (1974) pointed out that for the suburban train traffic the cruising regimes could be neglected. This further simplification allowed them to derive a suboptimal algorithm for real-time computation. They also formed the basis for the first DAS implemented in board computers of the Berlin S-Bahn (suburban trains) in Germany at the beginning of the 1980s.



Strobel, Horn and Kosemund (1974) implemented their algorithm that improved adherence to timetables and drove energy savings of approximately 15% when compared with the result of computer-aided train operation with manually controlled train movements in a train simulator. However, the technical optimal energy savings by computing or algorithm will be higher than are achieved in practice, as not all the drivers without DAS drive as fast as possible. Milroy (1980) also applied the PMP on urban railway transport and concluded that the three driving regimes in the optimal driving strategy for urban railways on level track and with a fixed speed limit are (as shown in Figure 4):

1. Maximum acceleration (MA),
2. Coasting (CO), and
3. Maximum braking (MB).

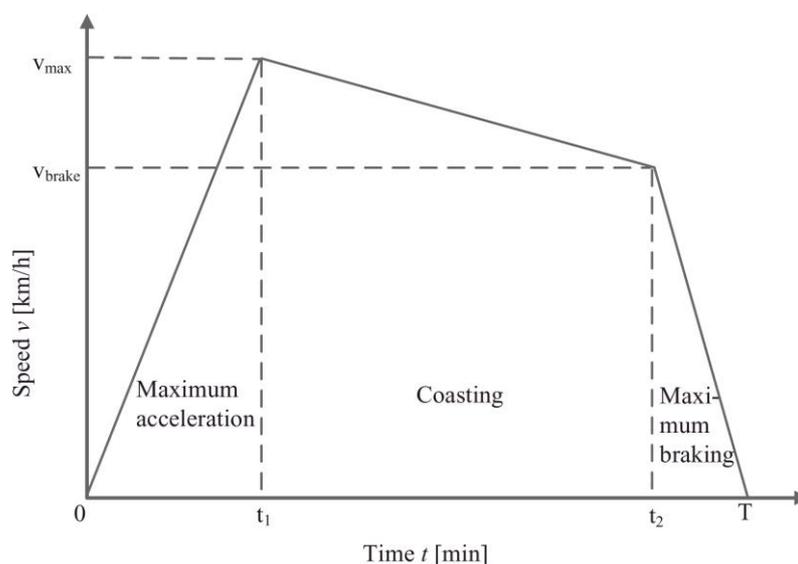


Figure 4: Optimal driving regimes without cruising (for metro and suburban railway systems) over time, with switching points between driving regimes at t_1 and t_2 .

(Scheepmaker, Goverde and Kroon, 2017)

Howlett (1990) proved PMP optimal driving strategy mathematically. Howlett and Pudney (1995) implemented the continuous energy-efficient train control theory in a commercial system named Metromiser, which can be used in urban, regional and freight operation with more than 15% energy saving achieved. The system consists of a software package for timetable planners to generate energy-efficient timetables and a DAS for energy-efficient train operation.

In 2002, Albrecht and Oettich used Simulink to numerically calculate switching curves that could be used to calculate the switching points in the optimal trajectory

backwards from the target station based on the algorithm from Strobel, Horn and Kosemund (1974). It was applied successfully in a DAS on the train driving simulator at Dresden University of Technology (TU Dresden), and in real-time passenger operation at the suburban railway line S1 in Dresden (Albrecht, 2005) which showed 15% to 20% energy savings compared with manual driving.

The information from DAS advice to the driver is calculated to limit the maximum speed, to minimise braking and to use the traction system (including regenerative braking) at its most efficient power setting. Asnis et al. (1985) studied the energy efficient train control problem including regenerative braking for level track. The regenerative braking has been introduced to urban railway transport optimal system by Adinolfi et al. (1998) with energy saving obtained from recordings at peak values up to 21%. And the average daily energy savings of simulation model of the traction system is about 13%.

For stop & go urban rail systems, the use of regenerative braking has a great energy saving potential, as approximately 50% of traction energy may be dissipated during braking phases. González-Gil, Palacin and Batty (2013) have pointed out that the implementation of timetable optimisation may significantly increase the interchange of regenerated energy between vehicles, which can lead to a reduction of between 3% and 14% of the total consumption in the system and the peaks of demand. González-Gil et al., (2014) further discussed the combination of optimising the timetable and applying driver advisory systems to provide efficient traffic control systems to maximise the interchange of regenerative braking energy between vehicles, which might lead to 15–20% energy consumption and driver advisory systems to minimise resistive losses in the power supply line could contribute 5–10% reductions. In metro operation, most lines are equipped with train control command system that cover not only ATP as with mainline railways (ERTMS...), but the full range of ATP-ATO and even in many case ATS. This means that trains motion (traction, coasting and braking) is controlled by the control-command system and NOT by the driver (GOA2 and 4). This is true at single train level, but also increasingly at fleet level used on a given line. This means that eco-mode time-tabling optimisation is embedded in the train running design in order to maximise braking energy recuperation (train A requiring traction power when train B is braking on the same substation section).

In Light Rail operation, operation is mostly performed by the driver on line-of-sight principle. In this case DAS system could be welcome for supporting drivers and



eco-mode driving training. As it is impossible to synchronise multiple train operation in LRT, on-board or way-side ESS are increasingly considered as a way to minimize braking energy waste.

Chao et al., (2017) proposed an effective and practical method, integrating a multipoint coasting control solution (without regenerative braking energy) so as to realize energy saving with a relative rise in time. MPGA is adopted to solve this multi-point combinatorial optimisation problem. Through the build and simulation a multi-particle train model based on the real line condition of Shanghai line 7 in urban transportation, the real condition of train and a time optimal train running reference curve is designed to be optimized for energy saving. The optimised reference curve can achieve a substantial reduction in energy consumption with time rising slightly. Compared with Standard Genetic Algorithms (SGA), the evolutionary process of MPGA also shows that MPGA can obtain quicker convergence and better fitness.

Freight

The traction of most freight trains is controlled using discrete throttle settings. It needs to consider energy-efficient train control models where traction control is restricted to a finite number of discrete values. In particular, this changes the cruising regime since not all control settings are possible to maintain an optimal constant cruising speed. Additionally, for freight trains, the distance between two stops is much longer than for urban trains and therefore some kind of approximate cruising phase would be the dominant phase. The models and algorithms for discrete throttle control setting were used in a DAS named Cruisemiser (Benjamin et al., 1989), which extended the ideas of Metromiser to long-haul freight trains in Australia. Cheng and Howlett (1992) applied the energy-efficient train control problem with discrete throttle settings. This is shown in Figure 5, where the cruising is approximated by alternating between maximum acceleration and coasting which leads to a saw tooth pattern between two speeds V and W , where a train repetitively accelerates to some critical speed W and then coasts until a certain critical speed $V < W$, where it will accelerate again to the critical speed. Howlett and Pudney (1995) extend it to urban and regional train.



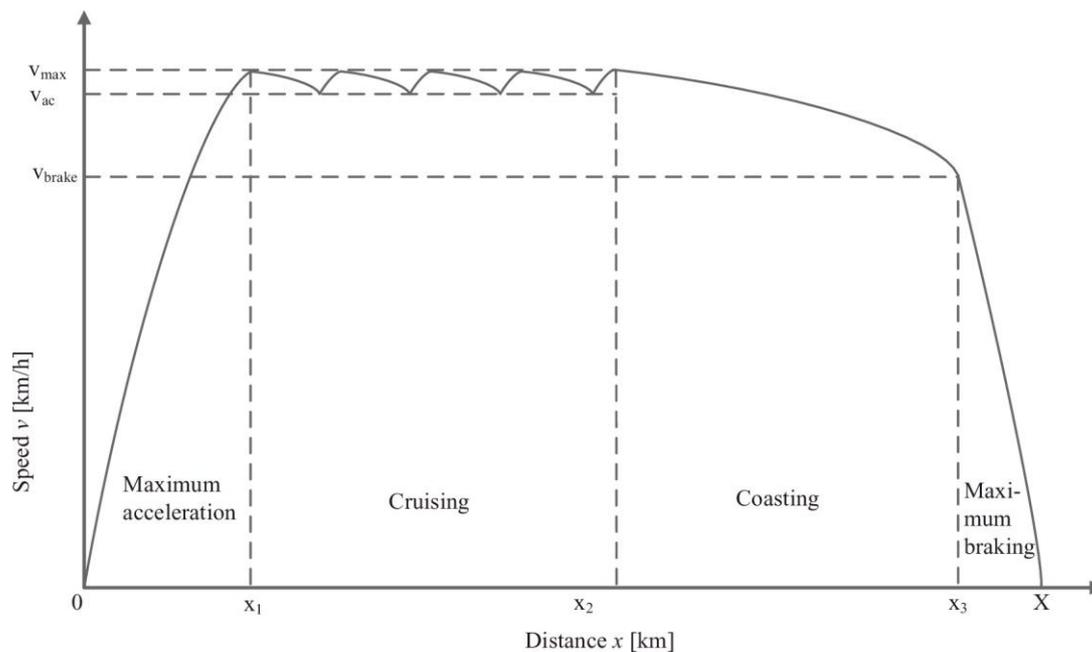


Figure 5. Speed profile of an energy-efficient driving strategy with discrete control (throttle settings) with switching points between driving regimes at x_1 , x_2 and x_3

Liu and Golovitcher (2003) derived the above five driving regimes from the PMP where the cruising regime is split into partial power and partial braking. The optimal speed-distance profile for a level track is illustrated in Figure 6. Based on these optimal driving regimes, the control switching graphs and the complementary optimal conditions, developed by a numerical algorithm, computes the required speed based on the remaining time and distance. This control algorithm computes the required speed based on the remaining time and distance, then constantly compares with the energy-efficient algorithm and re-calculates the optimal trajectory to the next station using the track gradient profile to find the optimal speed and locations for switching the control.

Vu (2006) also considered the optimal train control problem in speed and time as function of distance and showed that the optimal control for a specific journey on a non-steep track is unique. A steep uphill section is a section in which the train has insufficient power to maintain a cruising speed when climbing, while a steep downhill section is a section in which the train is increasing speed when applying coasting.

Howlett, Pudney and Vu (2008) have developed trial tests for freight trains with DAS Freightmiser in Australia and India in the period between 2002 and 2007, the results achieving about 15% energy savings when compared without this DAS.

Freightmiser was also tested on a passenger high speed line in the UK with energy savings of 22% compared to normal operation by Coleman et al. (2010). Future research by Howlett, Pudney and Vu (2009) developed a new local energy minimisation principle to calculate the critical switching points on tracks with steep gradients. They showed that a maximum acceleration regime is necessary for a steep uphill section and a coasting regime for a steep downhill section. The necessary conditions defining the optimal switching points near steep gradients are also necessary conditions for minimisation of local energy usage subject to a weighted time penalty. This was adopted as a more efficient strategy to compute the optimal switching points in the DAS Freightmiser for freight trains.

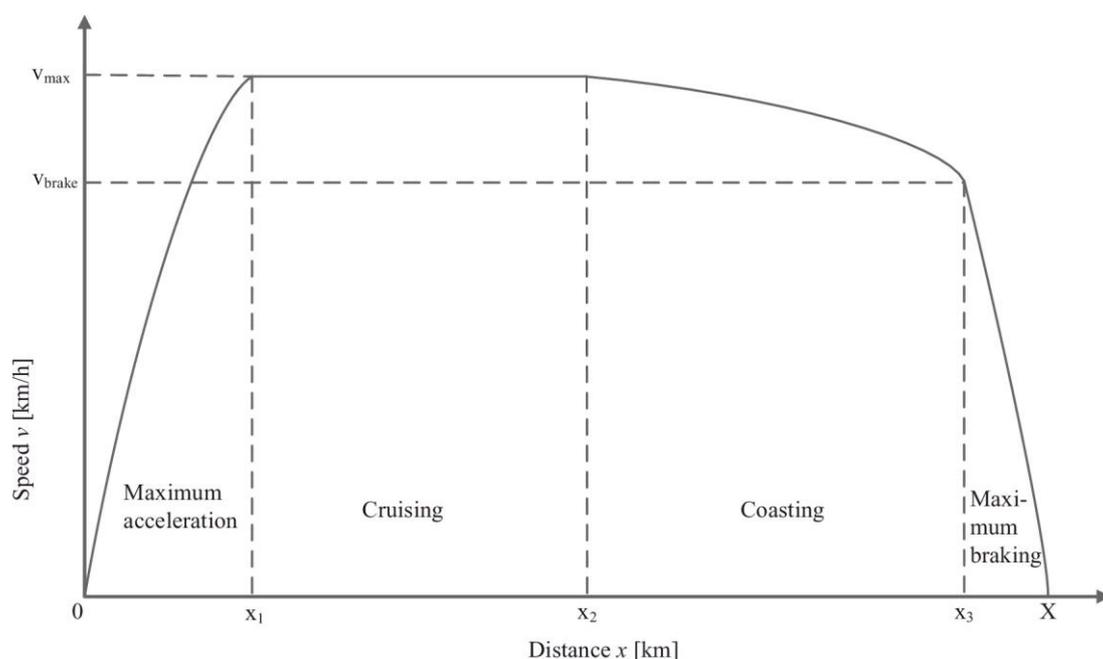


Figure 6. Speed profile of a basic energy-efficient driving strategy with switching points between driving regimes at x_1 , x_2 and x_3 (Liu and Golovitcher, 2003)

Aradi et al. (2013) used a predictive optimisation model to calculate the energy-efficient speed profile taking into account varying gradients and speed limits. A. Albrecht et al. (2013) have proved that the switching points obtained from the local energy minimisation principle are uniquely defined for each steep section of track and therefore also deduced that the global optimal strategy is unique. This algorithm Energymiser in a DAS for freight train has been implemented and resulted in energy savings between 7% and 20% compared to normal driving without Energymiser (Albrecht et al., 2015a). Further research by Albrecht et al. (2014)

showed numerical examples for urban, freight and regional train using Energymiser the optimal train control strategy indeed consists of maximum power instead of partial power for acceleration. The power is then applied for a smaller time resulting in a lower total energy consumption. Albrecht et al. (2015b) applied Energymiser on French railway undertaking SNCF (Société Nationale des Chemins de fer Français) TGV high speed trains using tablets to display driving advice to the train drivers.

Regional

The solution approaches considered so far first derived the optimal driving regimes from the necessary conditions for optimality using PMP, and then tried to solve the resulting optimisation problem of finding the optimal sequence and switching points of the optimal driving regimes by solving the differential equations of the train movements for the optimal driving regimes. But with varying gradients and speed limits it is very difficult to solve, while the inclusion of regenerative braking makes the problem even harder to solve.

Qu, Feng, and Wang (2014) proposed, in actual operation for real-time calculation, that the reference speed curve needs on-line recalculation when the operation circumstances change, such as delay or a temporary speed limit. An energy-efficient operation optimisation model with arbitrary feasible initial and final velocities is built, and the optimal operation modes are obtained by means of the maximum principle. When the braking energy is fully recovered, the speed-holding operation mode is proven to be the most energy-saving regime. Therefore, the optimal driving strategy consists of a sequence of the three driving regimes maximum acceleration, cruising and maximum braking, see Figure 7.



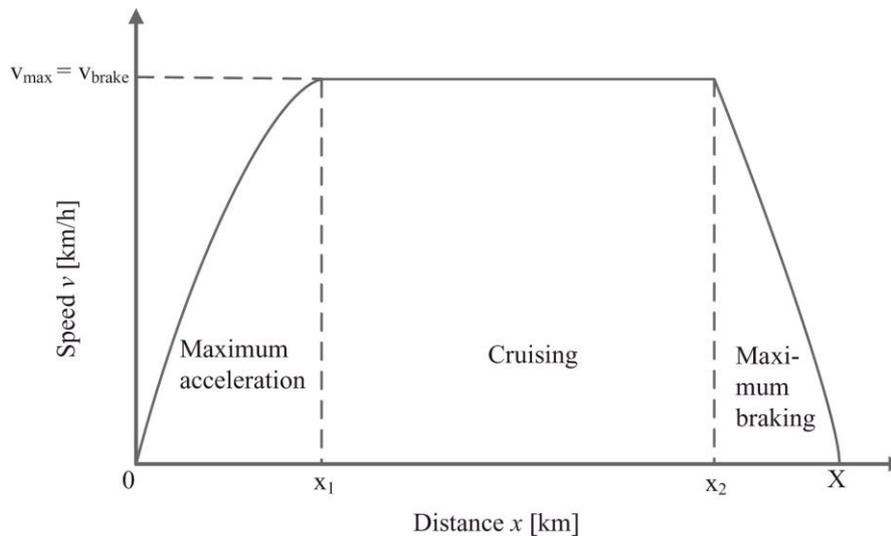


Figure 7. Speed profile of an energy-efficient driving strategy without coasting and with switching points between driving regimes at x_1 and x_2

In the ON-TIME project, an iterative algorithm was developed for an on-board DAS to calculate the optimal control of a train (ON-TIME, 2014a). The three options to increase the running time on a subsection with given start and end speed are:

- 1) Reducing the duration of maximum acceleration and replacing it with cruising at a lower speed or coasting;
- 2) Reducing the duration of cruising;
- 3) Replacing part of it by coasting; and reducing the cruising speed.

Results on a case study on the Dutch railway network between Utrecht Central and Eindhoven showed energy savings of 20% to 30% by the use of the algorithms compared to non-optimised train driving.

Wang et al. (2015) presented a method to consider the EETC with the state variables speed and time as function of distance and varying gradients and speed limits, under real-time rail traffic management and timetable constraints using the Train Path Envelope (TPE) to model intermediate stops as mandatory target points and through passing of stations as time windows. This model was applied to a case study based on the 50 kilometres long Dutch regional train. That shows the optimal trajectories use coasting before all scheduled target points and speed restrictions, while for the time-window case a smoother operation was obtained with a constant cruising speed over all intermediate stations. The case with the time windows saves 4.5% extra energy. The computation time for time-window case was less than 30 seconds for the entire trajectory.

Scheepmaker and Goverde (2015) developed an energy-efficient train control model in MATLAB called EZR and applied it to a real case. This model determines the energy-efficient driving strategy by calculating the optimal cruising speed and coasting point based on the knowledge of the optimal energy-efficient driving regimes obtained from PMP. This model gives results in terms of energy use which are close to the theoretical optimum. A significant energy savings of 15.1% by using the UZI method instead of the time-optimal driving strategy (technical minimum running time). This EZR model can save 19.6% energy when using the energy-efficient driving strategy compared with the currently used UZI method. Further results show that 5.5% and 9.4% extra savings can be achieved with the UZI method or energy-efficient driving strategy for the uniform distribution instead of the current distribution. This uniform distribution of the running time supplements leads to extra energy savings and an improvement on punctuality compared to the method of tightening the timetable. An example of an energy-efficient speed profile including varying gradients and speed limits can be found in Figure 8. This method could be used for static energy-efficient speed advice with optimal cruising speed and coasting point information for punctual trains.

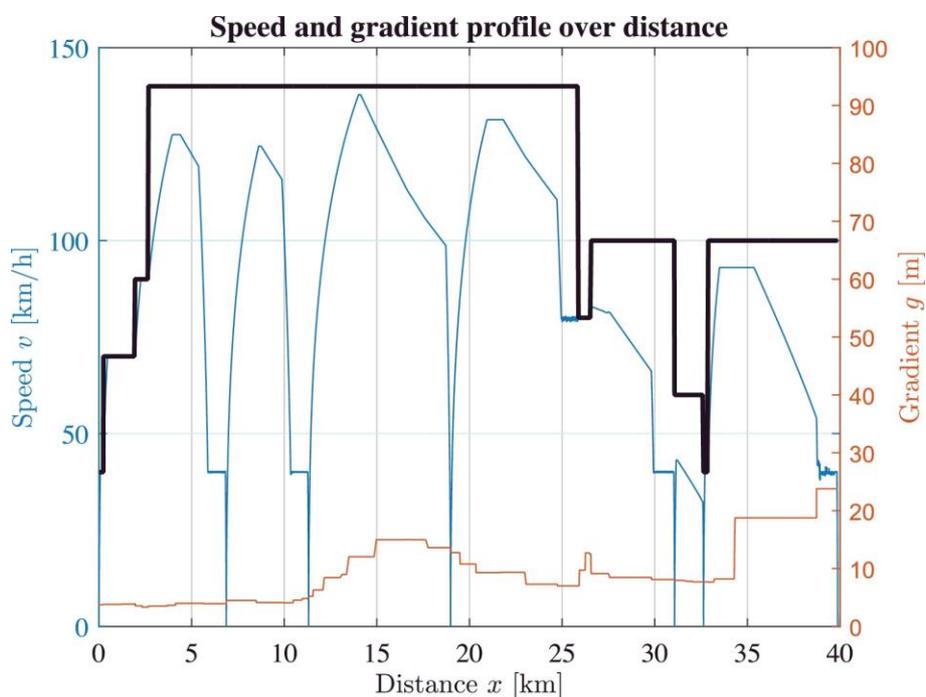


Figure 8. Example of an energy-efficient speed profile with varying gradients and speed limits. (Scheepmaker and Goverde, 2015)

High speed

Sicre et al. (2010) presented a method which combined simulation and optimisation techniques to optimise the energy consumption of a single manual-driving train service through best energy efficient driving strategies and efficient scheduling along a high speed line. It is simulated to obtain the run time and energy consumption Pareto curves of each stretch between two stations. Then the simulator will distribute the available slack time for the service among the stretches, which will minimise the overall energy consumption of the service.

Later in 2014 Sicre et al. proposed a Genetic Algorithm with Fuzzy parameters based on the accurate simulation of a train motion to determine the optimal driving strategy for delayed high-speed trains. Fuzzy cruising speeds and switching times were provided to the driver for manual train driving. This structure replaced the cruising regime by a partial traction phase that maintains a speed as long as traction is required.

The operation speed of High-Speed Train (HST) is much faster than other types of train and the distance between two adjacent stations of high-speed railway is much further than subway. The current research about automatic train operation (ATO) in subway system mainly concentrates on optimising an energy efficient speed profile and designing control algorithms to track the speed profile (Su et al., 2014; Yang, et al., 2016). In practice, the traditional automatic driving method increases the energy consumption and impairs the intelligence of train operation of the HST. (Cheng, et. al., 2017). The control process of HST is more difficult and complex than other types of rail system. For some unpredictable factors, such as weather conditions, line construction or equipment failure, real-time performance is also very important for the control system of HST.

Therefore, the previous research for HST is focused on optimizing the train schedules with the energy-saving constraint to determine an optimal operation strategy (Su et al., 2013; Yang et al., 2013). For example, based on optimal control theory and a joint optimal algorithm, Scheepmaker and Goverde (2015) developed mathematical optimisation model to optimally distribute running time supplements in the timetable by incorporating energy-efficient train operation into the railway timetable. Considering both the energy saving and the service quality, a two-objective integer programming model with headway time and dwell time control is formulated to find the optimal solution by designing a genetic algorithm with binary encoding (Yang et al., 2014). Considering the optimisation of energy



consumption and travel time as the objective on the basis of the coasting control methods, simulation-based methodologies and genetic algorithm are integrated to reduce the calculation difficulties and seek the approximate optimal coasting control strategies on the railway network (Yang et al., 2012).

3.3 Energy-efficient train timetabling

Mills, Perkins, and Pudney (1991) first studied a different version of EETT to reschedule trains, to solve the meet-and-pass problem of single track railway network for freight trains in Australia as result lateness and energy consumption are minimised. This model is a non-linear optimisation model for determining energy-efficient speed profiles and tested on a railway corridor between Port Augusta and Tarcoola (Australia), with savings of 6% energy consumption.

The first research of EETT and dynamic train operations was Albrecht and Oettich (2002), they used a simulation model to compute the energy utilisation for each discretised running time between two consecutive stops of a train. Then they calculated the optimal timetable with Dynamic Programming of the total running time of each train optimally distributed along the line. The developed method was successfully tested by Albrecht (2005) leading to 15–20% reduction in energy consumption compared to the use of the normal time table at the suburban railway system of Dresden in Germany.

Ding et al. (2011) considered the driving regimes acceleration, coasting, and braking used a two-level iterative optimisation model to determine the energy-efficient driving strategy and the optimal timetable for a metro line with a reduction up to 19.1%.

This optimisation model was further developed by Su et al. (2013) to determine both an energy-efficient driving strategy and an optimal distribution of the running time supplements in the timetable of a metro line, based on the gradients of the curves between running time and energy consumption. The energy consumption can be reduced on average by 10.3% by advising train control in the current timetable compared to normal operation, and reduced another 14.5% with a modified timetable. Su et al. (2014) extends an integrated energy-efficient optimisation model considering the headway times between consecutive trains in order to incorporate passenger demand and multiple trains in the Beijing Yizhuang metro line. The energy consumption could be reduced by 25.4% during peak hours



and 15.9% during off-peak hours, compared to normal operation and reduced by 24.0% over a whole day.

Sicre et al. (2010) considered optimising the running time distribution in order to minimise the total energy consumption for a high speed train, which computes the relation between the amount of running time supplement and the energy consumption. This then advises the energy-efficient driving strategy or optimal driving regimes driving to be driven. It resulted in a reduction of 33.6% of energy compared to the use of the commercial timetable with technically minimum running times over a high-speed journey. Cucala et al. (2012) further optimised the model of Sicre et al. (2010) which was the first to use a Genetic Algorithm and a simulator to solve an EETC problem for high speed trains.

Yang, Liden and Leander (2012) presented a connected DAS named CATO (Computer Aided Train Operation), which allows real-time data communication between trains and train control centre in combination with a centralised system for the calculation of optimal train movements. It allows both train drivers and train dispatchers the exceptional opportunity to optimise energy efficiency, punctuality and capacity utilisation from a global perspective. The results have proven reduced energy consumption by 15-25%, increased traffic capacity by 5-15%, as well as improved punctuality and reduced wear of vehicles and infrastructure. The implementation of CATO for freight train line in northern Scandinavia achieved energy savings of up to 25% and capacity increases of up to 15%. Furthermore, CATO has also been installed on the high-speed trains of Stockholm/Arlanda airport, where the system currently operates in stand-alone DAS (Yang, Liden and Leander, 2012).

Even more, the energy consumption can still be reduced by up to 10%. Binder and Albrecht (2013) also studied a combination of timetabling and energy-efficient train operation for regional trains for the European rail project ON-TIME (ON-TIME, 2014b). Then they developed a Dynamic Programming algorithm which considers stochastic dwell times, but the running times are assumed to be deterministic. The optimal energy efficient driving strategy for the running time are obtained by fixing the arrival and departure times.

Wang and Goverde (2016) considered the train trajectory optimisation problem for two successive trains with varying gradients and speed limits, operational constraints, and signalling constraints of mixed regional and nonstop intercity train. A local signal response policy ensures that the train makes correct and quick



responses to different signalling aspects such as train with S-DAS that is not connected to a TMS, a global green wave policy aims at avoiding yellow signals and thus proceed with all green signals which are available and corresponding to a DAS connected to a centralised TMS, which monitors and predicts the movements of the trains and communicates the corresponding earliest signal approach times to the following trains. In this case the train trajectory is recalculated to track the possibly adjusted timetable with the aim of minimising delays and energy consumption. This work has been designed for real-time train trajectory calculation to support a driver advisory system.

3.4 Conclusion of energy optimisation

Research on the energy optimisation by train control was developed based on PMP then further developed different algorithms for particular operation solutions. All mainline rail modes are considered with an emphasis on urban and regional railway systems. To compute realistic speed profiles, it is important to take into account nonlinear train traction and resistance, line resistance within particular varying gradient profiles, and varying speed limits.

The differences between the different types of rail transport are mostly related to the maximum speed of the trains and the distance between two stations. When the average distance between two stations increases the cruising becomes more important for energy efficient driving control. For short distances, the maximum speed cannot be reached and the running time supplements of the timetable are very small, so reaching the optimal speed to start coasting is more important. Provided the EETT is aiming to optimise speed profiles of trains and optimally distribute running time supplements over the successive train runs in order to minimise the energy consumption, it also maximises the use of regenerative braking energy.

DAS provides stable driving advice of an optimal driving strategy to the train driver or specific driving regimes, including switch time of coasting or cruising at less than the speed limit. The algorithms in the existing DAS and ATO systems rely on some simplifications to be able to compute (sub)optimal driving advice in real-time or are based on offline computed solutions for a broad set of scenarios (Scheepmaker, Goverde and Kroon, 2017). Therefore, by using efficient algorithms and simplifications of the problem when a train is connected to IM's Traffic Management



system or offline computations of a set of solutions that can be chosen, fast calculated algorithms are needed to realise a real-time connected DAS.



4 CONCLUSIONS

This deliverable D4.1 report summaries the main functionalities and characteristics of S-DAS and C-DAS systems and their suitability to energy management and optimisation of driving strategies. Specifically, to identify, assess and compare the operational concept of these two systems and their relevance to the four operational scenarios.

From the perspective of energy optimisation algorithms, strategies, and models to improve energy efficiency for the railway operation system, it appears that all theoretical models are a foundation to find the optimal driving strategy. DAS is a practical resolution for delivering optimal solutions to the driver and enables a communications link to the IM control centre. The simulation complexity and time increase for the models when more realistic behaviour is included, like varying gradients and speed limits. Therefore a more advanced algorithms operation and faster algorithms for a real-time DAS are needed.

The optimisation method by DAS can be very different according to train system, operation condition, travelling time, delay, energy system, safety etc. and implies different solution approaches and systems. In addition, the more advanced DAS might not only involve more efficient algorithms, optimised driving strategies and models, but also include improvements to the interface, interaction and acceptability with the driver.

C-DAS introduces a real-time operation control for any type of rail service into the DAS concept. It links train driver execution, provides feedback and accepts dynamic timetable to optimise an on-time efficient operation strategy under any operational condition. It aims to harmonise individual driver behaviour to the whole system. Therefore more efficient models and faster algorithms are required.

There are increasing needs for operators to implement more advanced DAS to improve their current energy optimisation strategy. The potential of energy optimisation on railway operation system is developing rapidly in a short period of time and can achieve significant energy saving from 1% to up to 33%. The prospect of improving DAS especially Connected DAS is promising.



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