railways; smart infrastructure; ERTMS; power grid management;
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SMART RAIL INFRASTRUCTURE, MAINTENANCE AND LIFE CYCLE COSTS

Summary. This paper discusses smart railway infrastructure systems. The meaning of "smart" is described followed by a discussion on the benefits of the use of smart infrastructure. Some key components of smart infrastructure, few examples and case studies are presented. Our analysis suggests that the implementation of a smart system may well lead to energy savings of 25%, therefore smart systems should be implemented in larger scale.

INTELIGENTNA INFRASTRUKTURA KOLEJOWA, UTRZYMANIE I KOSZTY CYKLU ŻYCIA

Streszczenie. W artykule poruszono zagadnienia inteligentnych systemów infrastruktury kolejowej. Znaczenie słowa „inteligentne" jest wielokrotnie poruszane w kontekście korzyści płynących z użycia inteligentnej infrastruktury. Zaprezentowano kilka kluczowych elementów, składających się na inteligentne systemy, przykłady technologii oraz ich wprowadzenie w życie codzienne. Nasza analiza wykazała, że wprowadzenie inteligentnych systemów infrastruktury może prowadzić do oszczędności energii rzędu 25%, w związku z czym powinny one być wdrożone na większą skalę.

1. INTRODUCTION

What is smart rail infrastructure?

Infrastructure is basic physical structures needed for the operation of a society or enterprise, or the services and facilities necessary for an economy to function. It can be generally defined as a set of interconnected structural elements that provide framework supporting a functional entity.

The term typically refers to the technical structures such as roads, bridges, water supply, sewers, electrical grids and telecommunications. Infrastructure can also be defined as “the physical components of interrelated systems providing commodities and services essential to enable, sustain, or enhance social living conditions”.

As defined in the 2009 TEN-T Green Paper, transport infrastructure consists of three major components: built or physical infrastructure, smart infrastructure and vehicle communication. The smart infrastructure refers to all the communication and IT equipment that provide support for the implementation of Intelligent Transport Systems and Services (ITS).

Nowadays, the crucial technological ingredients include low-cost sensors and clever software for analytics and visualization, as well as computing firepower. Smart infrastructure is reliable and ITS can contribute towards a more efficient, safe and environmentally friendly transport system for all modes of transport.

Europe needs a safe and cost effective transport network to encourage movement of goods and people within the EU and towards major markets in the East. This is central to European transport, economic and environmental policy. Many parts of Europe's rail network were constructed in the mid-19th century long before the advent of modern construction standards. Historic levels of low investment, poor maintenance strategies and the deleterious effects of climate change has resulted in critical elements of the rail network such as bridges, tunnels and earthworks being at significant risk of failure. The consequence of failures of major infrastructure elements is severe and can include loss of life, significant replacement costs (typically measured in millions of Euros) and line closures which can often last for months.

What are the benefits?

Smart infrastructure has the potential to transform rail transport management by enabling a greater understanding of the interconnectivity of systems and the implications of events resulting in improved reliability, safety and efficiency.

Key considerations in the development of a national smart infrastructure for all modes of transport include:

- Security/safety-inform traveler about routes, facilities, accidents, infrastructure works, events;
- Manage traffic like congestions, speed and access;
- Manage incidents;
- Privacy, interoperability across databases, maintenance, governance and leadership;
- Reduction in service affecting incidents;
- Reduced cost of routine maintenance;
- Improved reliability;
- Reduction in reputational risk.

2. KEY SMART INFRASTRUCTURE COMPONENTS

In this chapter we present the key components and systems of the smart infrastructure used for railway transport. We first analyze one of the oldest and most used components – track circuits. Then we also describe the components of ERTMS and the characteristics and requirements for power grid management.

2.1. Track circuits

Intelligent transport systems (ITS) are widely used in railway transport. One of the benefits of ITSs are increasing train operational speeds and increasing track capacity while maintaining high levels of safety. That is because ITS is designed based on a safety-oriented approach.

(Fig. 1) [4] represents the decision-making process and all possible outcomes of such an approach. There are three possible situations [4] that may occur:

- TRUE means that system works correctly and the response of the system corresponds with reality (e.g. track is unoccupied and lights signal green).
- FALSE Positive means acceptable error of the system which can occur. If the system does not receive the correct information, the response of the system must be positive. That is the only way to ensure the safety of the system.
- FALSE Negative refers at that error which causes crashes. System signals are safe situation but in reality is the opposite.

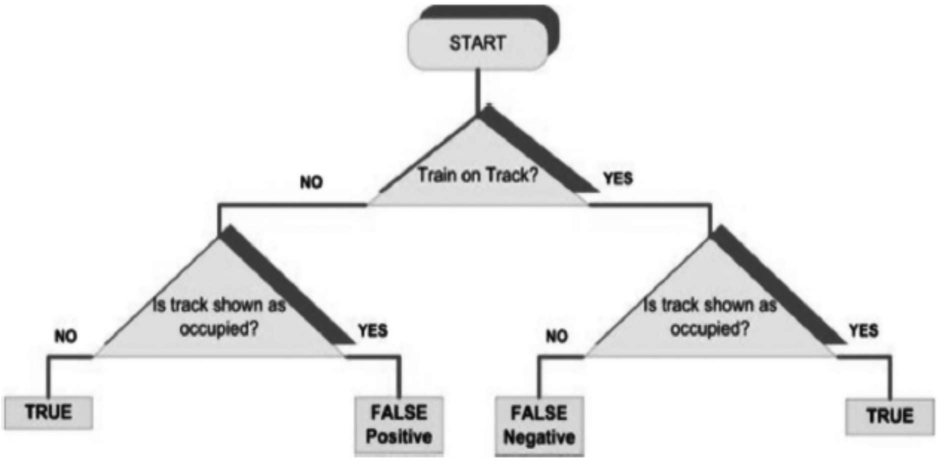

Fig. 1. A True and False States' Diagram
Rys. 1. Schemat blokowy stanów odcinka obwodu torowego

In 1872 W. Robinson (the American inventor, electrical engineer, mechanical engineer and businessman) invented the first closed track circuit used in railway signaling. [3] Track circuit enable to detect train presence on separated track blocks. The Fig. 2 shows the basic principle.

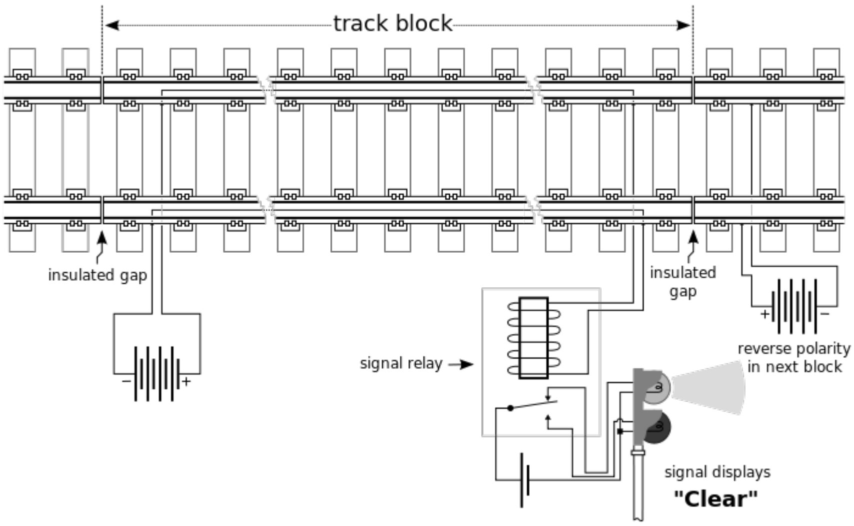

Fig. 2. Schematic drawing of track circuit for unoccupied block
Rys. 2. Schemat budowy sygnalizacji wyzwalanej przez obwód torowy dla niezajętego odcinka

When there are no trains, the signal relay is energized by current flowing from the power source through the rails and signal lights show green light – it means "clear" way. When a train is present (Fig. 3), the axles of the train interconnect rails and signal relay is de-energized. Trains move form right to left on the picture and system signals for another train to slow down or stop.

What follows is a brief outline of basics components and types of track circuits. [1] As was partially described on the previous pictures, track circuits consist of:

- battery (source of supply),
- regulating resistance,
- track relay,
- fuses (protective device),
- choke (protective device for AC electrified area),
- track lead cable,
- continuity rail bond,
- insulation rail joint;

and could be divided into several sub-groups according the following aspects.

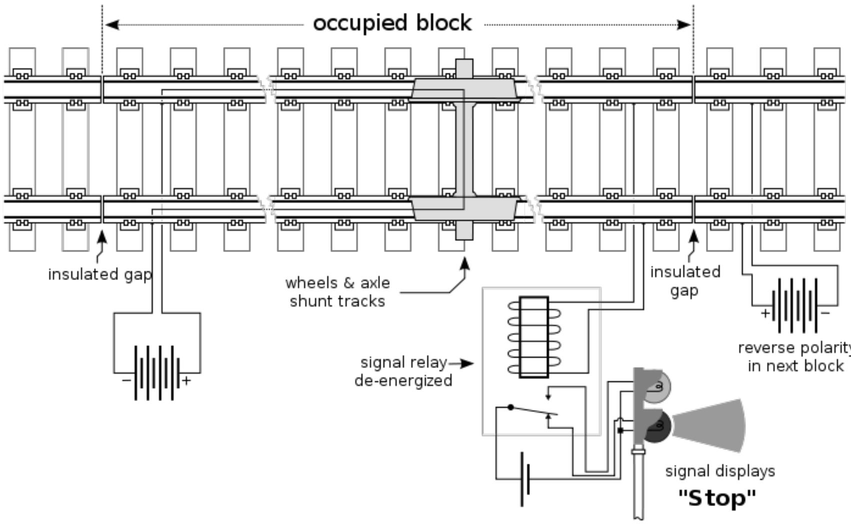

Fig. 3. Schematic drawing of track occupied circuit
Rys. 3. Schemat budowy sygnalizacji wyzwalanej przez obwód torowy dla zajętego odcinka

a) With respect to the source:
   - **D. C. track circuit** – the source of supply is direct current (DC). Commonly used in non-electrified lines and electrified lines with 25 kV AC.
   - **A. C. track circuit** (varied frequencies) – used alternating current (AC) signals instead of DC. The AC signal can be un-coded or coded and then the inductive pickups equipment is required.
b) With respect to signal:
   - **Un-coded track circuit**
   - **Coded track circuit** – the current going from the power-source is modulated and then the equipment on the train for detection is required.
c) With respect to traction return current:
   - **Single rail track circuit**–single rail is available for installation of insulated joints in order to define track circuit boundaries and the second rail carries traction return current.
   - **Double rail track circuit**–there are insulated rail joints in both rails which will carry both propulsion and signal currents.

2.2. European Rail Traffic Management System (ERTMS)

European Commission decided [6] to support the implementation of a harmonized standard for the railway signaling system and replace the national systems with a unique European system – ERTMS. This system has also been adopted in several projects outside Europe, such as in South Korea, Taiwan, Algeria, Argentine and New Zealand. The ERTMS is composed of two basic components: [7]

- ETCS (European Train Control System) is an automatic train protection system, which monitors and adapts train speed according to information received from the trackside. ETCS slows down the train automatically if the maximum permitted speed is exceeded.

- GSM-R (Global System for Mobile Communications – Railway) is a radio system that allows the exchange of information (speech and data communication) between the track and the train and the train and Radio Block Center (RBC).

The ETCS has been designed with three application levels which determine different manners of interaction between the track and the trains.

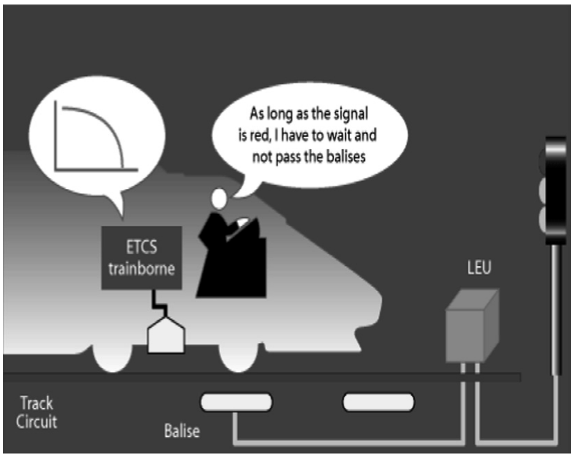

Fig. 4. ETCS Level 1
Rys. 4. ETCS Poziom 1

ERTMS level 1 (Fig. 4) [13] is designed as an add-on to or overlays a convectional line already equipped with lineside signals and train detectors (track circuits). Communication between the tracks and the train is ensured by balises located on trackside at required intervals and connected with the train control center. The main benefits brought by ETCS Level 1 are interoperability and safety.

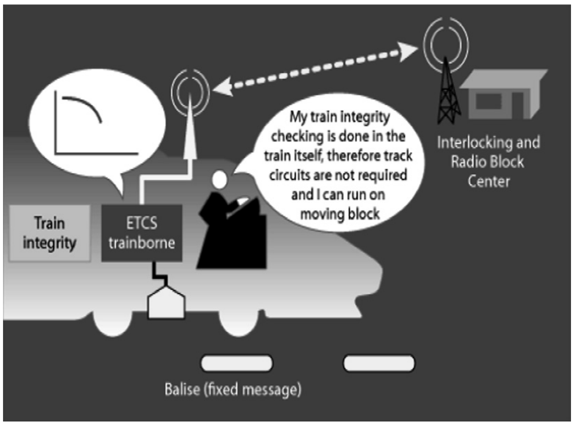

Fig. 5. ETCS Level 2
Rys. 5. ETCS Poziom 2

ERTMS level 2 (Fig. 5) [13] does not require lineside signals, compared to level 1. The movement authority is communicated directly from a RBC to the on-board unit using GSM-R. In this case the balises transmit only "fix messages" about location, gradient, speed limit etc. Thanks to removal of lineside signals could be greatly reduced maintenance costs. The main benefit of the ETCS Level 2 is increase of line capacity by enabling higher operational speeds.

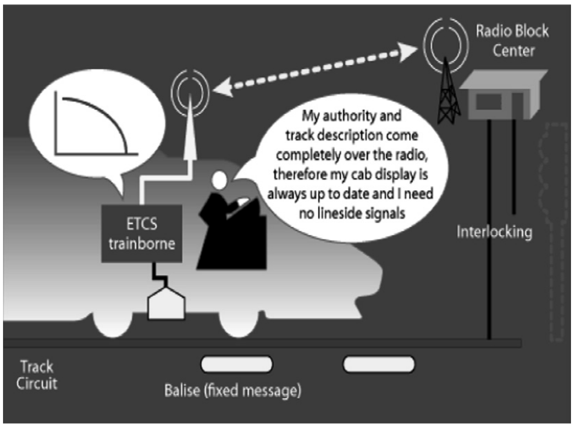

Fig. 6. ETCS Level 3
Rys. 6. ETCS Poziom 3

ERTMS level 3 (Fig. 6) [13] introduce the moving bloc, as opposed to levels 1 and 2 which set fixed blocs (section of track between two fixed points which cannot be used by two trains in the same time). The train rear end location as well as the integrity status are send to the RBC by train itself and any other train detection system by the trackside is no longer required. The ETCS Level 3 leads to the next optimization of line capacity.

2.3. Principle of operation about Eurobalises

A balise is an electronic transponder placed between the rails of a railway as part an Automatic Train Protection (ATP). Balises constitute an integral part of the European Train Control System. A balise which complies with the European Train Control System requirements is called as Eurobalise. No power source is needed for a typically balise. A standardized transmission protocol is used by the Eurobalise S21. This is based on the transmission method on introductive coupling and data transmission with frequency shift keying and has been used successfully for years by Siemens for train control purposes. Eurobalise S21 is activated when a train passes and a low-power signal is emitted. This information is used by the EVC (on-board computer) for train supervision purposes and serves as basic for the data displayed on the DMI (driver-machine interface) in the driver's cab. Siemens Eurobalise S21 is used to transmit data for locating and train control purposes to the vehicle at any point along the track. Eurobalise S21 is easy to install due to its small dimensions and weight.

There are 2 available variants which can be applied:

- Every time when a train passes a permanently stored telegram transmits the same data to the balise antenna aboard the vehicle.
- The second variant of Eurobalise S21 is the variable-data balise, transmits variable data according to the signal aspect. This is controlled by a lineside electronic unit (LEU) which is connected via a permanently attached cable without plug.

Location and train control purposes to the vehicle at any point along the track is made by the Eurobalise S21. This can be used for main-line and mass transit railway all over the world. Installation is easy to do due to its small dimensions and weight. The balise is typically mounted on or between sleepers or ties in the center line of the track.

2.4. GSM-R

GSM-R standardize railways, industry and commercial operation since more than 10 years - provides operational and commercial advantages to railways and makes them more competitive in a changing environment. Thanks to GSM-R railway communication works without system borders (interoperability) and costs are reduced (efficiency):

Table 1

Benefits of GSM-R

MAIN BENEFITS	
Interoperability	**Efficiency**
- Increase average travel speeds through optimized breaking points - Guaranteed high speed (500 km/h) and conventional lines operation - Seamless border crossing - Increase maximum speeds with line of sight signals replaced with radio - Increase track capacity through minimized inter train distance	- Reduce infrastructure cost by using widely adopted GSM technology - Reduce infrastructure cost through competition - Only one Radio system for all applications including ETCS - Standard products available off the shelf

GSM-R uses characteristics of the GSM system (identical or similar to those), such as frequency spacing (200 kHz), modulation (Gaussian minimum shift keying, GMSK) and access type (TDMA, TDD/FDD). The frequencies of GSM-R are extended below the frequencies of the GSM-900 standard.

GSM-R guarantees a high level of reliability and accessibility based on long term experience. Provides dedicated engineering processes and optimal control system. It is able to detect errors in real time and to prevent incidents. Fall back available into public networks (manual or automatic switch over between 900 & 1800 MHz GSM band). This system will be introduce in 56 countries by the end of 2016 (Fig.7-8) [14].

Fig. 7. GSM-R network development plans (1998-2016)
Rys. 7. Plany wprowadzenia systemu GSM-R (1998-2016)

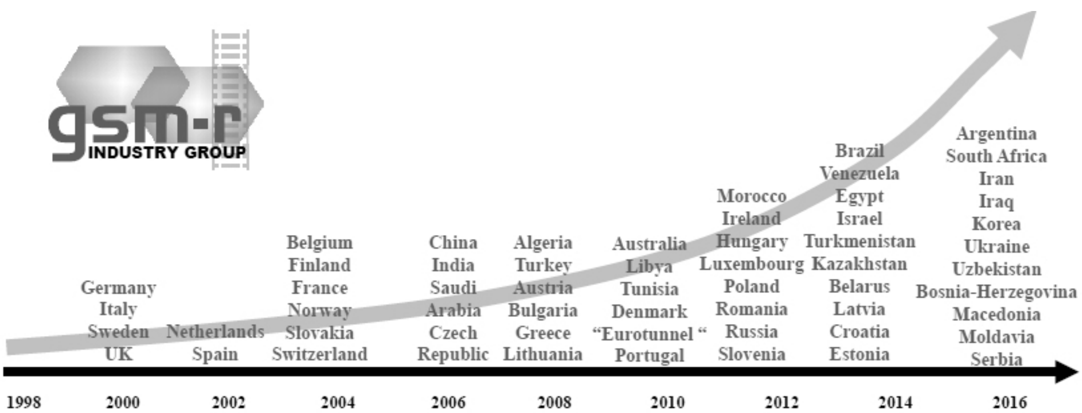

Fig. 8. GSM-R system availability and projects in preparation
Rys. 8. Dostępność systemu GSM-R i projekty w przygotowaniu

2.5. Power grid management

Despite that the use of energy by the European railway sector is efficient in comparison with others modes of transport, the European Rail Research Advisory Council (ERRAC) defines how to focus research efforts of the European railway industry in order to face increased emphasis on energy efficiency and environmental impact. [9]

One of the solutions is dynamic braking system that means conversion of kinetic energy into electricity and, in contrast to friction braking, does not generate wear and tear, heat or sound. Today widespread way of using this system is rheostatic braking, which the regenerated electricity dissipates in banks of variable resistors. The second option, called regenerative braking, is reusing regenerated electricity within the transport network itself. [8]

In order to maximise the use of recovered energy and minimise the need of resistors for dissipating we can take two different approaches. The first one is to equip trains with energy storage systems (ESSs) that accumulate the regenerated energy and release it for the next acceleration phase (Fig. 9) [8]. Another consists in improving receptivity of the network.

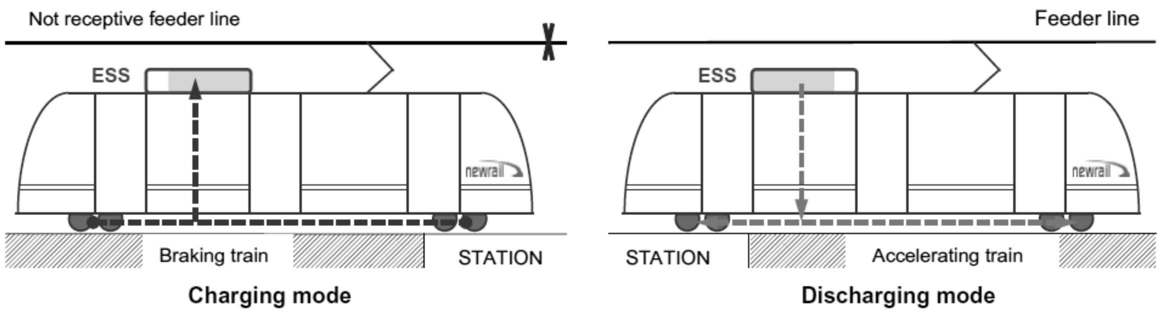

Fig. 9. Schematic of on-board ESSs operation in urban rail
Rys. 9. Zasada działania pokładowego systemu ESS na przykładzie wykorzystania w kolei miejskiej

The recovered energy from one vehicle may be returned into the power supply line for use of another accelerating vehicle in the same electric section (Fig. 10) [8]. To increase efficiency of this model the synchronisation of acceleration and deceleration of trains by optimising scheduled timetables is needed.

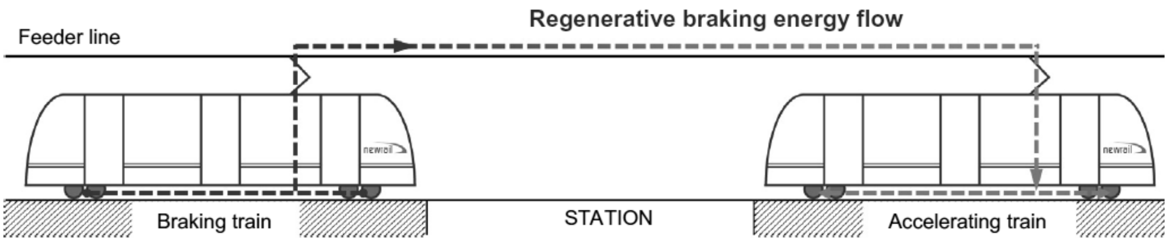

Fig. 10. Schematic representation of regenerative energy exchange between trains
Rys. 10. Zasada działania systemu rekuperacji energii elektrycznej pomiędzy pociągami

Batteries could be placed on the train itself or at the track side. These stationary ESSs absorb the braking energy of any train in the system and deliver it when required for other vehicles' acceleration (Fig. 11) [8]. The battery could be larger than in the case of on-board ESSs conversely the efficiency is lower because of line losses.

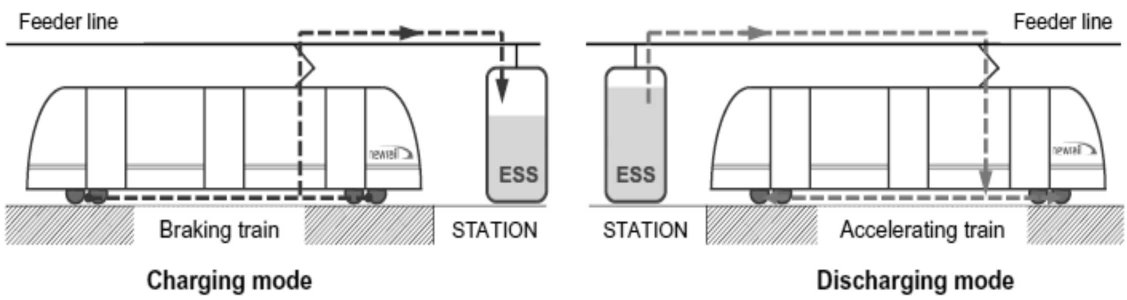

Fig. 11. Schematic of wayside ESSs operation in urban rail
Rys. 11. Zasada działania systemu ESS wykorzystując stacjonarne punkty ładowania w kolei miejskiej

Another option to improve the receptivity of the line is to use reversible substations with DC/AC inverters enabling bidirectional operation so that the regenerated energy can be fed back to the medium voltage distribution network (Fig. 12) [8]. The energy could be used for lighting, escalators, offices, etc. or could be sold back to the energy provider.

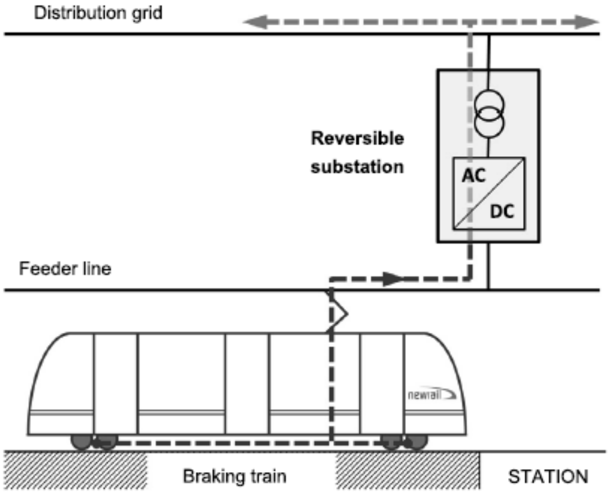

Fig. 12. Schematic of reversible substations in urban rail
Rys. 12. Schemat podstacji falownikowej w kolei miejskiej

3. EXAMPLES AND CASE STUDIES

Information and communication technologies are applications of IT that help to float the traffic, optimize operating costs, prevent delays and help in planning maintenance in railway transport. All this tools should be improving safety, increasing efficiency and reducing negative impact on society and environment (Tab. 2) [4]:

Table 2

Benefits of ITC tools

Improving safety	Increasing efficiency	Reducing negative impact on society and environment
Accident management: - Detection; - Monitoring; - Management; - Providing information (in real time);	Monitoring traffic (having a real time view on the situation and on main traffic characteristics);	Reducing risks on routes;
Traffic management: - reducing the occurrence of congestion; - controlling speed on routes; - controlling access;	Planning trips on the route – transport resources management;	Reducing pollution and noise;
Safety management emergency activities (by use communication channels) and emergency call;	Monitoring fleet and freight;	Reducing time for transport - minimizing travel time for passengers and freight;

Implementation and improvement travellers information about incidents, weather conditions and any works on the route;	Redirect vehicles on less crowded and more safety routes;	Integrating all transport systems - contributing positively to society;
Providing on-board functions e.g. virtual signals and driver behaviour;	Providing support for multimodal transport;	Improving routes infrastructure – influence on environment;

The following describes few examples of smart infrastructure utilization in the Europe even in the world. There are some examples of interoperability in Europe with GSM-R, ESS systems in Tehran metro line and more.

3.1. ARRIVAL method

An example of an ICT tool used for supporting railway operations is ARRIVAL (Algorithms for Robust and online Railway optimization: Improving the Validity and Reliability of Large scale systems). It focuses on two important and actually undiscovered aspects of planning that pose even harder optimization questions: robust planning and online (real-time) planning. These two, tightly coupled, facets constitute a proactive and a reactive approach, respectively, to deal with disruptions to the normal operation.
Scope of actions:

- New Models for Robust and Online Planning;
- Robust Network and Line Planning;
- Robust and Online Timetabling and Timetable Information Updating;
- Robust and Online Resource Scheduling;
- Delay Management.

It has already been successfully implemented in The Netherlands, Germany and Switzerland. For example, ARRIVAL algorithms were used to make a new timetable for the Dutch national railway system which handles 5500 trains per day; it is now one of Europe's most efficient and reliable railway networks. In Berlin, the waiting time between trains on the U-Bahn underground network has been reduced from 4 to 2 minutes thanks to the application of ARRIVAL algorithms. Swiss railways have implemented an optimal planning schedule, based on ARRIVAL algorithms, for additional trains on high-risk corridors where both freight and passenger trains operate. [10]

(Fig. 14) [10] shows all possible connections between Berchtesgaden Hbf and Westerland in Germany. Grey colour represents the edges of the railway timetable. Black colour shows the part of the graph visited by an algorithm. The resulted query path is shown in white. The left map show classical approach application and the right one show the algorithm developed by ARRIVAL researchers - a small amount of black lines, more efficient solution of the connection.

3.2. ESSs in Tehran metro

Figure 15 [11] shows the speed cycle of the train in Tehran metro line 3 (between 10 stations). We can see from the diagram that the train must accelerate and decelerate approximately each every two minutes. This is the reason why ESSs are most commonly used in metro systems. [11] In this study was calculated with application of stationary super-capacitors energy storage in each metro station with appropriate configuration. The daily energy saving will be 25% and total investment will be returned after 10 months.

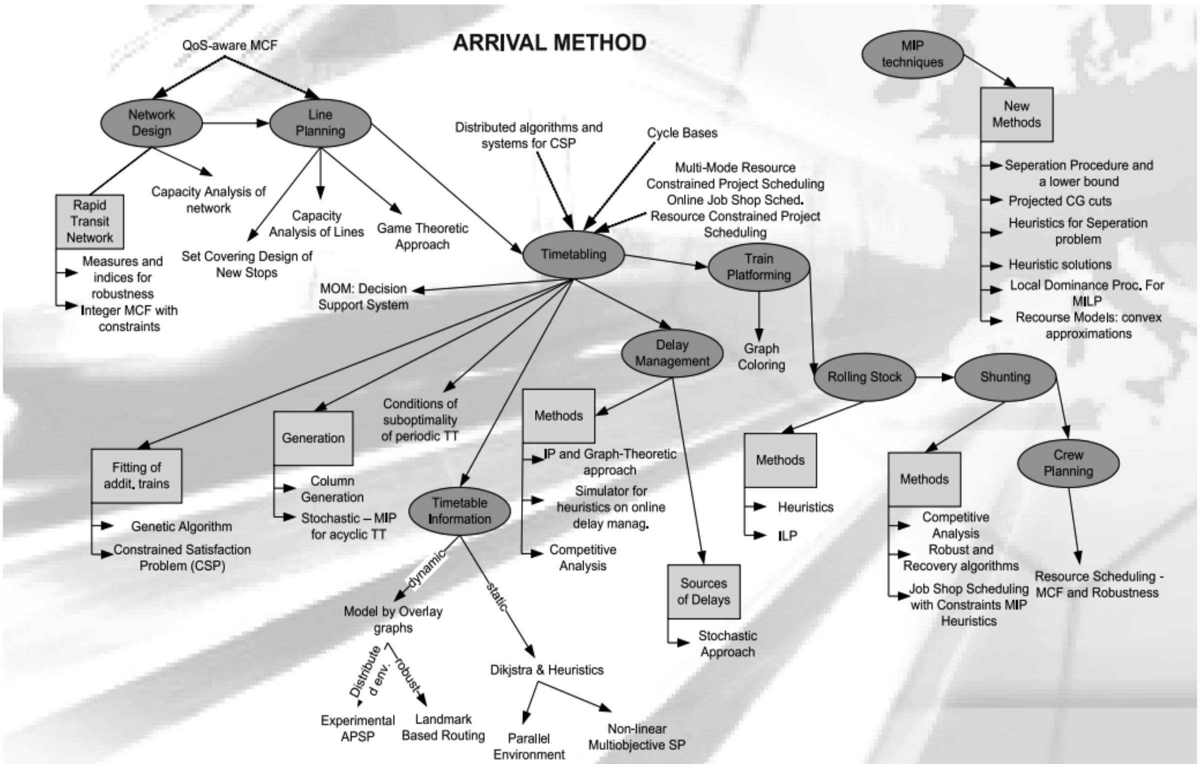

Fig. 13. Connections between ARRIVAL elements graph
Rys. 13. Schemat blokowy zależności pomiędzy elementami algorytmu ARRIVAL

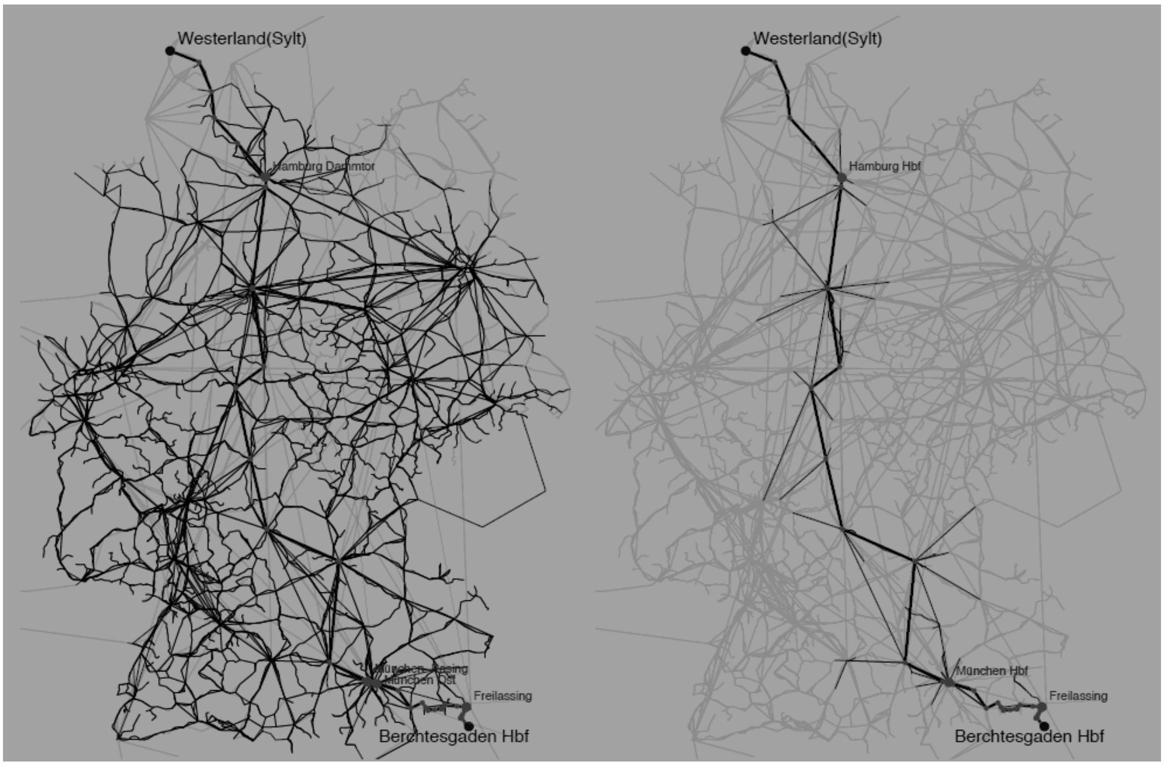

Fig. 14. All possible connections between Berchtesgaden Hbf and Westerland in Germany graph
Rys. 14. Schemat wszystkich możliwych połączeń kolejowych pomiędzy stacjami Berchtesgaden Hbf Westerland w Niemczech

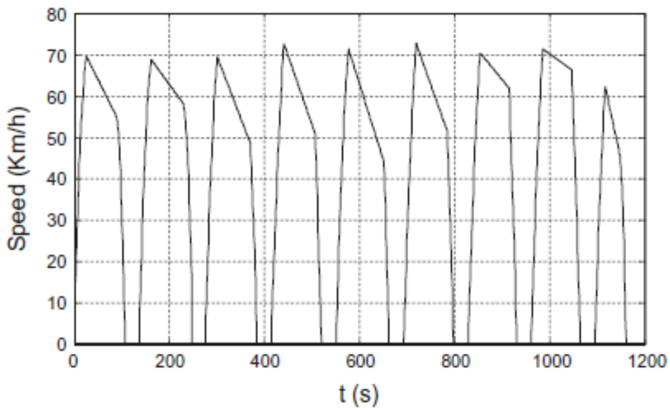

Fig. 15. Speed cycle of train, speed-time graph of 10 stations
Rys. 15. Cykl prędkości pociągu, wykres prędkość/czas dla 10 stacji

3.3. Implementation of GSM-R system in Poland

The Polish railway plans to convert its railway network gradually to GSM-R, thus until 2020 Poland plans to have 15.000 km of railway lines with GSM-R technology. Currently Centralna Magistrala Kolejowa (CMK), also known in Poland as the Rail Line No. 4, is completely equipped with GSM-R technology, for ETCS Level 1 (Fig. 16, nr 2) [13].

Ongoing implementation of ERTMS/GSM-R in Poland, section:

- Legnica – Węgliniec – Bielawa Dolna – 84-kilometres, the first GSM-R project in Poland
  Poland plans to install ERTMS/GSM-R on the railway network, by 2015 as follows [fig. 16, nr 4];
- Kunowice – Poznań – Warszawa, part of ERTMS Corridor F, - implementation foreseen by December 2014;
- Warszawa – Gdańsk – Gdynia, implementation foreseen by June 2015 [fig. 16, nr 1];
- Legnica – Wrocław – Opole, part of a Corridor F extension – expected implementation: 2013-2015 [fig. 16, nr 3];
- Warszawa – Łódź – implementation expected by 2014.

Fig. 16. Map of implementation ERTMS/GSM-R system in Poland
Rys. 16. Mapa przedstawiająca wprowadzanie systemu ERTMS/GSM-R w Polsce

4. CONCLUSIONS

In this paper we looked at smart rail infrastructure where all communication and IT systems make the railway transport more efficient, safe and environmental friendly. The right way to achieve these objectives is through understanding the interconnectivity between the technical aspects of the system, the application of knowledge and the implementation of promising results from research.

The objective to make railways sustainable and cost-effective imposes the necessity to consider a wide range of problems, availability of smart infrastructure included. It requires the use of ICT-based devices that can make the maintenance process easier and improve traffic reliability, safety and efficiency, which eventually leads to reduction of life-cycle costs.

It has been shown that smart systems could improve the service significantly. Basic system for detection of train presence, which appeared over 100 years ago, will be probably replaced by ERTMS. This unique European system is implementing by individual countries and e.g. Poland will have 15 000 km of line with GSM-R technology until 2020. That makes European railway more interoperable. ERTMS also affects reduction of maintenance costs (no lineside signals is needed anymore), allows operation with high speeds levels, provides communication between the vehicle and track or control centre, which means better traffic management and informing passengers.

There have been presented different methods of utilization regenerative braking in the chapter about power grid management. The smart power grid management leads to reduction of power consumption in railway and makes it more environmental friendly. It can be concluded that energy saving about 25%, especially in metro lines, can be achieved by utilising ESSs. When the effective system for time-tabling (e.g. ARRIVAL) is used at the same time, the efficiency can be higher.

To experience significant benefits from smart rail infrastructure, smart systems should go beyond national boundaries and be implemented in larger scale.

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