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DEMAND RESPONSE AND ENERGY STORAGE: A PORTFOLIO TO MANAGE RAILWAY POWER SYSTEM PEAKS DUE TO SYNCHRONIZED TIMETABLES

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ABSTRACT

The objective of this paper involves the analysis and the study of opportunities for the management of Railway Power Systems demand through some models and tools well known in Public Power Systems: Physically Based Load Models and Distributed Energy Resources (load management, on-board generation and energy storage). The paper considers exciting trends for the development of railway transportation driven by energy policy scenarios and the developments of modern and refurbished power units (e.g. last-mile capacity). Moreover, the management of Railway Power System can support the necessary flexibility of the main Power System to enhance the flexibility of the system while improving the integration of renewable. The paper is focused on the use of two possibilities: the control of HVAC loads in trains and the use of on-board generation of trains with last mile capacity to manage the demand and, in this way, face to the problem of synchronized timetables which causes high power peaks in railways. Results justifies the opportunity to develop flexibility of railway units, which improves the social and economic of railway transportation.

KEYWORDS

Energy storage, regenerative braking, demand response, energy efficiency, DER modelling.

INTRODUCTION

The main concern of this paper is the analysis and evaluation of different possibilities offered by the technology for the management of loads and on board energy storage systems (ESS) used in railways (e.g. “last-mile” ability) in a similar way that public power systems are applying DR and ESS in the last decade, in the whole system, and especially in Smart-Grids. The idea is that basically that some trains can be a smart load or generator (railway prosumers) for the railway power system: trains can generate energy through regenerative braking, some modern trains and tramways include some capacity for on board storage and generation (hybrid units), and passenger trains have flexible loads (heating and cooling loads, i.e. HVAC) that can represent up to 10-20% of demand [1], including traction power. Moreover, efficiency in transportation is an important concern for public authorities [1].

The interest of railway operators to improve the service to their customers has evolved to the development of the so called “synchronized timetables”. The idea is that trains leave at the same minute every hour (e.g. 8h05, 8h35, 9h35,…) to make easier for the customer to remember and manage the possibilities to select its railway journey in an specific route. This idea has been applied in several countries in Europe (e.g. France or Germany) and some countries, such as Switzerland already has trains every half hour that connect the major population areas, but operators are evolving to the idea of raising this frequency to 15 minute by 2030-2050 [2]. In practice, this supposes that loads (trains) switch on at the same time and develop a high power demand to accelerate the train in a short time (some minutes). This synchronization can produce changes up to 300MW (in 5 minutes) on the demand curve of the Swiss Railway Operator (SBB-CFF) in the Zurich Area [3]. These problems are well known in Power Systems but with lower rates for demand increase (for instance, in the integration of PV resources). That is, the problem is even bigger in railways systems. For this reason SBB-CFF started in 2018 a study to evaluate the possibilities of DR in “power loads” [3] (HVAC loads in coaches).

For these reasons, the use of Demand Response (DR) and ESS portfolios must be considered as relevant in the near future in the framework of new electricity supply paradigm: Smart-Grids. According to this paradigm, the interaction of the Electric Power System (PPS) and the Railway Power System (RPS) should bring new opportunities to perform a better and more reliable operation of the overall energy system. The main contributions of this paper are two: first, the paper integrates different models for: main loads of trains (traction), secondary or auxiliary loads, and main ESS systems utilized in train units on board (OESS) to evaluate the flexibility of train's demand and their aggregation. Secondly, the paper demonstrates the potential of DER resources in railways to reduce load peaks and improve the operation of the RPS. The rest of the paper is organised as follows: Section II describes the scenario and methods used, explaining the models applied to simulate auxiliary loads and OESS systems. Based on these models, section III explains the possibilities of using Distributed Energy Resources (DER) such as ESS and DR (for traction and "auxiliary" loads) in order to reduce power peaks due to synchronization policies. Finally, some conclusions are stated in section IV.

SCENARIO AND METHODS

This section presents the scenario used for simulation and a review of the different methods being used in this paper. All of these methods are based in the search of physical knowledge in processes that drive the dynamic behaviour of the different elements of the system (capacitors, batteries, HVAC loads or tractive units). The reason for this choice is that this method allows easily the interaction with other tools developed for DR the literature, some of they develop by authors of previous papers [4].

Scenario: a terminal railway station

Terminal stations are very usual in France (Paris Montparnasse; Paris Gare du Nord), Switzerland (Zurich Hbf, Luzern), Germany (Munich), Italy (Milano, Roma) or Spain (Madrid Atocha and Chamartin). In these stations, intercity and regional trains are placed in the platforms up to 20 minutes before they leave the station to allow check-in for travellers or the connection with other trains. In this case, trains require power for auxiliary loads and are able to store energy (from regenerative braking of other units that arrive in the station) or generate power from storage devices. Table 1 shows a timetable for one medium-size station: Luzern (CH), with traffic of 96000 pas/day. As it can be observed there are several train arriving to the station (and, logically aply braking, regenerative in this proposal) and others are ready to leave. The main characteristic of the timetable shown in table 1 is that is the same for every hour from 5 a.m. to 10 p.m. This strategy (synchronization) is usual in Switzerland, Germany or France in last decades. It has advantages for the user (simplicity) but some problems for the management and operation of trains (inflexibility). Another problem is from the point of view of consumption because it involves a lack of flexibility of the time of use of the loads.

Table 1. Timetable for inter-regio (IR) and intercity (IC) services in the morning (hour 0X)

Arrivals			**Departures**		
Service	**Time**	**Origin**	**Service**	**Time**	**Destination**
IR 15	0Xh 00min	Bern	IR 15	0Xh 01min	Bern
IR 26	0Xh 05min	Basel	IR 70	0Xh 10min	Zurich
IR 75	0Xh 25min	Zurich	IR 26	0Xh 18min	Arth-Goldau
IR 27	0Xh 30 min	Basel	IR 27	0Xh 30min	Basel
IR 26	0Xh 32min	Arth-Goldau	IR 75	0Xh 35min	Zurich
IC 21 (1)	0Xh 41min	Lugano	IC 21 (1)	0Xh 54min	Olten
IR 70	0Xh 49min	Zurich	IR 25	0Xh 54min	Basel
(1): Not synchronized every hour					

With respect to trains, this work considers trains with the characteristics described in [5]. The reason is that main manufacturers (Bombardier, Alstom, Patentes Talgo or Siemens) supply similar train families for different EU countries (e.g. TRAXX series by Bombardier). The locomotives are considered of TRAXX series (6MW of rated power, 15kV/16.7Hz), coaches for IR services, and Electric Multiple Unit (EMU, 4MW of rated power) are used for IC services.
An additional reason to choose this scenario in Luzern, is that Swiss Railways (SBB-CFF-FFC) owns a small railway power system (RPS) which includes 6 hydroelectric power stations at 16.67Hz (a usual frequency for traction) which deliver power to railway substations at 15kV-AC. The problem is that this system is not an islanded one due to the growth of passenger and freight traffic in Switzerland (Swiss policies in transportation are a reference in Europe). Demand has increased demand in last decades, and SBB-CFF system needs an additional energy supply from Swiss Public Power System (PPS) through seven AC/AC converters (50Hz to 16.67Hz) [6]. Average demand of SBB-CFF operator is presented in figure 1a. According to data discussed in [6] demand exceeds 16.67Hz generation capacity (around 450MW) in the morning and the afternoon. These peaks are covered by frequency converters (figure 1a, dashed lines). An additional problem is that peaks in railways occur for a very short period of time, typically less than 1 minute

(20, 30 or 40s) due to acceleration and tractive characteristics of trains (notice that these peaks are not shown in figure 1a, because curve 1a is an hourly curve that filters demand changes, but these peaks will be shown in next section dealing with simulation). These peaks appear during time of peak traffic (7-8 a.m. and 6-9 p.m.) and involve changes up and down around 15-25MW/s which requires the use of additional power converters to cover these peaks (usually in winter). Notice that this scenario is worse the one power engineers have to face in PPS with peak infrastructures to cover the fluctuations of demand and that explains the interest for DR policies worldwide. It should be taken into account that these peaks stress PPS and that involves serious penalties for SBB-CFF operator: first the cost of converters to cover peaks zone (figure 1a, area from 600 to 750MW). Second: the cost of energy in markets in periods in where SBB hydro generators do not cover demand. Figure 1b depicts an example of energy costs in winter and summer periods according to EPEX day-ahead market data [7]. It can be seen that peak of demand follows peak of prices. Moreover intraday markets can reach up to 85-90 €/MWh in these periods [7], i.e. energy costs increase by 30-40% due to these peaks of demand. These conditions represent a typical scenario for applying DR policies that is being explored by SBB-CFF since 2018 [3] but restricted to coach heating loads and points heating systems in the track.

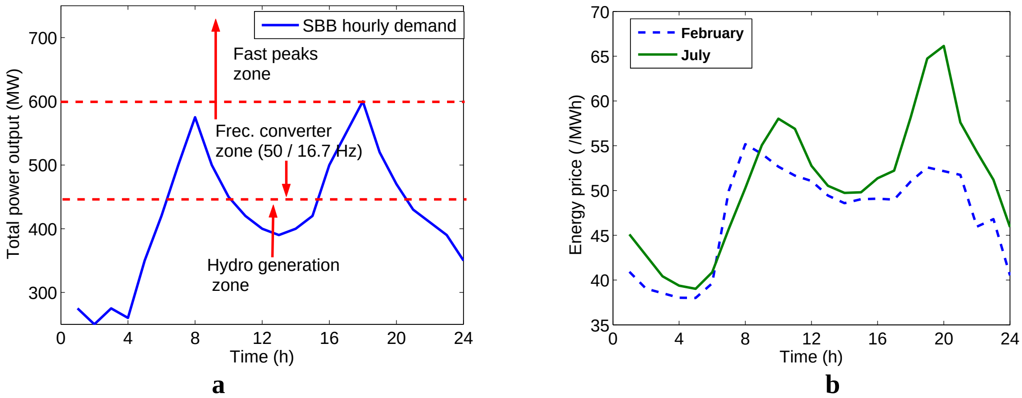


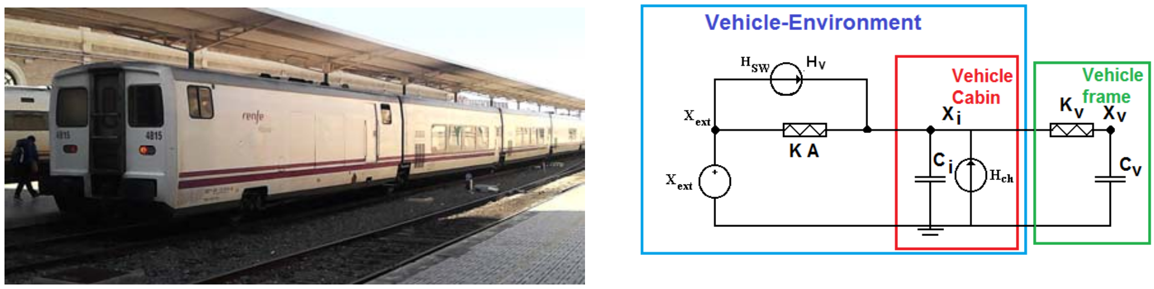
Figure 1. SBB-CFF System: **a)** Demand and generation mix covering demand **b)** EPEX day-ahead prices for a week (2019).

Heating, Ventilation and Air Conditioning (HVAC) loads in Railways

The methodology used in this paper is based on PBLM Models. The main idea is that heat exchanges in train coaches are similar to heat exchange in buildings. Moreover, energy conversion devices (electricity to heat) are quite similar: compressors, condensers and evaporators, even in their size. The models for HVAC loads in trains are based on previous developments of authors for similar loads in residential segments [8] and the works developed by Rail Tec Arsenal Fahrzeugversuchsanlage (Wien, Austria), a laboratory which is expert in climatic tests for transportation vehicles [9]. Authors have integrated both models for HVAC loads in train and have revisited a procedure to aggregate demand consumption of each HVAC units inside each coach of the trains (a similar procedure is used to aggregate residential loads to reach the minimum power reduction levels required in DR programmes by System or Market Operators [4]). An example of these PBLM models for a coach (figure 2a) is presented in figure 2b (rolling stock), and the state-space system representation is established in equation 1.

$$\begin{pmatrix} \frac{dX_i(t)}{dt} \\ \frac{dX_v(t)}{dt} \end{pmatrix} = \begin{bmatrix} -\frac{1}{C_i}\left[kA+K_V\right] & \frac{1}{C_1}K_V \\ \frac{1}{C_v}K_V & -\frac{1}{C_V}\left[K_V\right] \end{bmatrix} \begin{pmatrix} X_i(t) \\ X_v(t) \end{pmatrix} + \begin{bmatrix} \frac{kA}{C_i} & \frac{1}{C_i} & \frac{1}{C_i} \\ 0 & 0 & 0 \end{bmatrix} \begin{pmatrix} X_{ext}(t) \\ H_{SW}(t)+H_V(t) \\ H_{CH}(t) \end{pmatrix} \quad (1)$$

The model takes into account the external area of the vehicle (A), the global thermal transmittance coefficients (k outdoor, K_V indoor-vehicle) to the environment, the energy conversion by HVAC (H_{ch}), the heat capacities of vehicle (C_V and C_i ,i.e. the thermal storage capacities of each coach of the train) and the heat losses and gains through solar radiation and ventilation (H_{SW} and H_V). A more detailed explanation of these parameters can be found in [4].



a b

Figure 2. PBLM model of HVAC loads in a reference coach used in the paper **a)** Talgo IV coaches in Cartagena terminal station (operated by RENFE, Spain) **b)** 2R2C network electrical-thermal equivalent for these railway coaches.

On board Energy Storage Systems (OESS)

The response of two 500F Maxwell super-capacitors (SC) racks (16V, model BMODO500 P016 B02) and one Li-ion Battery (50V, 4kWh) have been tested in the UPCT laboratories. Conventional models for fast discharge of these elements, based on electrical equivalents, described in the specific literature [10], and also described in reports from railway research projects have been considered [11]. The reason for selecting these models (and not electrochemical models) is that they are quite accurate and, formally, very similar to models previously used for HVAC loads. This allows to use standard procedures, already developed for HVAC loads, for the identification of parameter (e.g. genetic algorithms), control or aggregation of devices, and also makes easier the integration of models with each other (for example, railway models). These systems are supposed available in power/service car/coaches or in locomotives for simulation purposes.

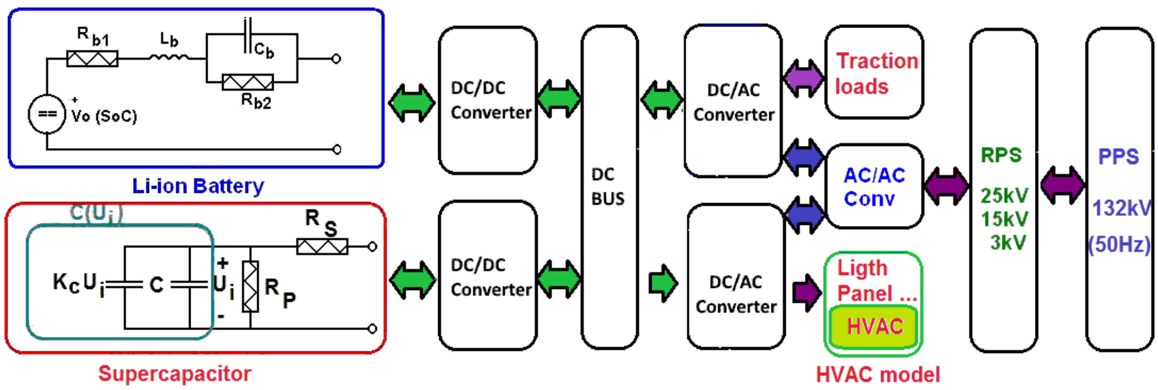
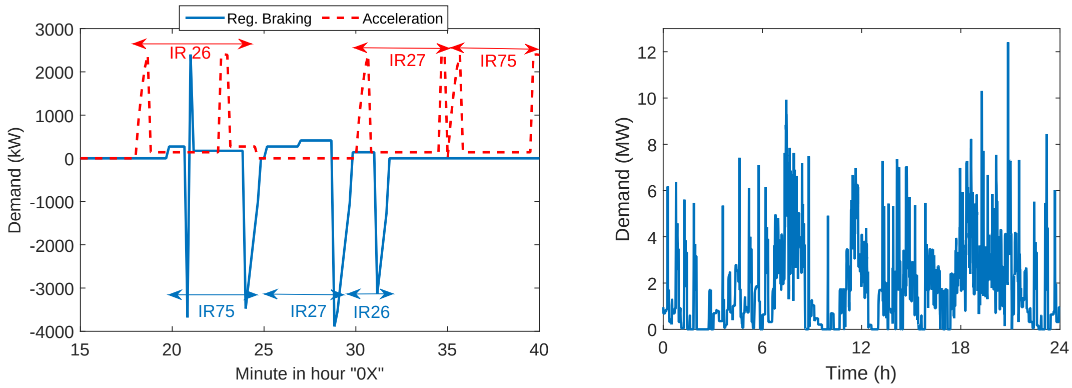


Figure 3. PBLM models for ESS to be used in the paper for simulation purposes (equivalent super-capacitor and equivalent battery) and their interaction with other models (traction and HVAC loads) and with Rail and Public Power Systems (RPS, PPS).

SIMULATIONS AND MAIN RESULTS

This paper entails and simulates the previously presented models. The energy requirements of tractive demand are necessary for defining the operation strategies of other resources (ESS and HVAC loads, figure 3) according to RPS state. These requirements can be evaluated through train simulators a well known topic in the literature. There are several options for the user in the market furnished by train manufacturers (Sitras by Siemens [12]) and universities (TrainOps by LKT, Sweden [13]. Authors have used their own simulator, presented in [5]. According to table 1 and the characteristics of trains, power requirements of some of the trains (IR services) are presented in figure 4a (notice that IR26 or IR75 are a type of service and not a specific train). A simulation of a substation is also presented in figure 4b. The sharp profiles in figure 4a explain the high rate of change in demand (in the order of some MW/min) which matches the data presented in [6] for the overall SBB system (up to 25MW/s).

For simulation purposes, it is assumed that some trains are of new facture and they include ESS devices or, in other cases, trains are refurbished (every 10-20 years) including some kind of ESS. To explain the management of DER resources (SC, battery and HVAC) IR27 service has been chosen (figure 4a) leaving Luzern at 0Xh 30min. The arrival of IR27 and IR75 (a different physical train but with the same number of service, IR27, figure 4a in blue colour) has produced around 31kWh of braking energy to be recovered by the SC bank and, at a minor extend by Li-ion batteries of the other IR27 (waiting its departure at 0Xh 30min, figure 4a, red dashed) and the service IR75 (leaving at 0Xh 35min, figure 4a, red dashed). The energy requirements of these trains are given in table 2. These accelerations explain the sharp peaks in the demand of the substation (figure 4b, e.g. time interval 7-8 a.m.). Notice that the success in the operation of both EES and HVAC will shave these peaks and the size of AC/AC converter (whose price ranges 600-900 €/kW).



a b

Figure 4. Demand and generation a) Demand for acceleration and generation through regenerative braking for trains leaving and arriving from minute 15 to minute 40 in hour "0X" according to table 1. **b)** Demand profile for a substation

Table 2. Braking regenerative energy in arrivals and energy needed for acceleration in departures (Figure 4)					
Arrivals			**Departures**		
Service	**Time**	**Braking energy (kWh)**	**Service**	**Time**	**Acceleration energy (kWh)**
IR 75	0Xh 25 min	31.3			
IR 27	0Xh 30 min	42.7	IR 27	0Xh 30 min	41.8
IR 26	0Xh 32 min	24.7	IR 75	0Xh 35 min	48.5

To store the energy generated through braking and supply enough energy to the departure of trains, it is proposed to install a Hybrid ESS (HESS): a SC of 10 kWh, and a bank of batteries of 20 kWh in each train. SC's target is to cover the high peaks of power needed to accelerate while batteries can supply the energy necessary to maintain velocity.

The proposed strategy is due to the acceleration requirements of train IR27 when leaving terminal station at 0Xh 30min. It is assumed that energy recovered through braking (IR 75 and IR 27) allows the recharge of SCs of units IR 26&27. When IR 27 leaves, SC and batteries of IR26&27 support its acceleration. Figure 4b show that this train accelerates in two steps: the first to 50km/h to leave platforms and points of station, and the second to reach 100km/h in the start of main track. Figure 5a depicts the power generated by SCs and batteries from IR 26&27, and the State of Charge (SoC) of both elements. It can be seen that SCs support main energy needs of IR27. Fortunately, another IR 26 is braking (punctuality is a benchmark of operator's quality) and fills both SCs. Once, SoC recovers the value 1 (100%) the IR 27 is able to accelerate until 100km/h (figure 5a, time 34min). In this case, IR 75 does not support generation anymore.

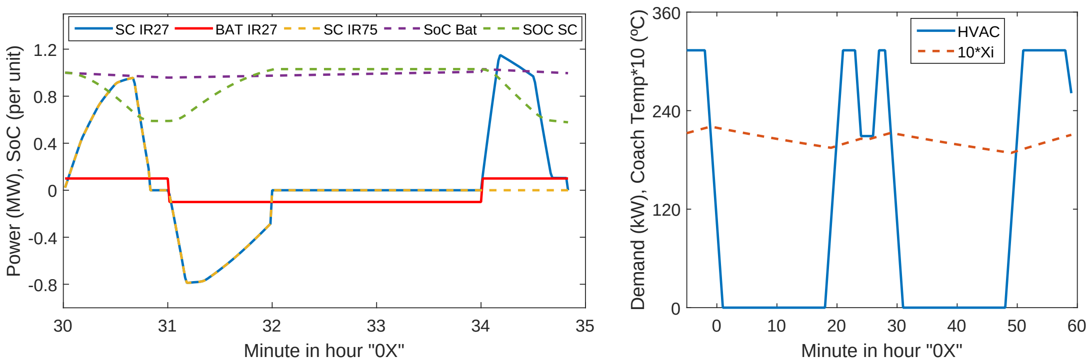


Figure 5. Strategies for DER resources: a) Supercapacitors and batteries of IR27 & IR75; b) HVAC loads of IRs (control of demand in kW, and internal temperature of coaches)

To improve the synergy of this policy, HVAC loads of trains leaving or arriving to station are controlled according to control policy depicted in figure 5b. Notice that the temperature of coaches remains above 20ºC and customer comfort is guaranteed. Summarizing up: IR needs 2.5 MW for its acceleration. From this quantity: 2MW are achieved by SCs of IR 26%27, 0.15 MW are found in batteries and 0.3MW in HVAC control, i.e. ESS and HVAC balance generation needs.

From an economic point of view, 2.5MW are saved in the substation during peak periods (figure 4b). This fact reduces the size of AC/AC inverters (800€/kW, including BoS [14]). Besides, the operator avoids the need to purchase energy in balance or intraday markets (around 20€/MW). With respect to units, authors estimate that 18 trains that operate in peak periods need to include HESS systems on board. The results are shown in table 3, and the proposal seems cost-effective at a pre-feasibility level.

Table 3. Cost and benefits of HESS & HVAC control configuration

Technology and capital cost (k€)	Peak reduction (kW)	Cost (k€)	Energy reduction (MWh/yr)	Benefit (k€)
HESS, SC (18 units)*78	2000	1404	132	5253
HESS, battery (18 units)*6	150	108	262	10506
HVAC control (18 units)*6	300	108	-	-
AC/AC 50/16.7inverter (1)*	2500	-	-	2000
Energy in short-term markets	-	-	43.8	8760

CONCLUSION AND POLICY IMPLICATIONS

This paper entails and simulates how well-known DER policies (DR and ESS) have been identified and simulated for Railway Power Systems. Train models, load models and ESS models have been revisited and linked to improve the usefulness of simulations results. Braking energy can therefore be recuperated by ESS and energy efficiency improved both in the Railway Power System and in trains. Moreover the use of load management and ESS avoids the problems related with high ramps experienced by demand in RPS systems due to synchronized timetables. This flexibility of load can be used in the integration of renewable in Public Power Systems. Finally, these alternatives appear as cost-effective, and can catalyze the development of railway transportation in EU and other countries (both for passenger and freight services), considering inter-modal approaches proposed worldwide, and especially between EU and Asia areas.

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