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Cost-effectiveness of Opportunity Charging in Non-electrified Railway Lines

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***Abstract*—This paper analyses the cost-effectiveness of deploying opportunity charging points in long-distance non-electrified railway lines, which are driven by battery-based hybrid diesel-electric railway vehicles. A study case based on a real railway line is presented, where potential locations for the charging points are proposed. With the aim of developing a comprehensive sensitivity analysis, for each combination of charging points locations the life cycle costs of different energy management strategies and lithium-ion battery technologies are also compared. Additionally, for each case the optimal size of the powertrain elements is calculated. In order to develop the proposed analysis, a methodology based on an optimization approach is presented. The obtained results demonstrate that deploying opportunity charging points along the route is a feasible solution, as long as appropriate strategies and battery technologies are used. In the best scenario, the life cycle cost of a base case without charging points can be reduced a 4.3%, and the cost of a traditional diesel-electric vehicle a 7.6%.**

***Index Terms*—opportunity charging, energy management, life cycle cost analysis, lithium battery, railway engineering**

I. INTRODUCTION

Considering that the relation between the produced CO_2 emissions and the carried passenger activity is lower than in road transport, railway mobility emerges as an additional opportunity in the path towards decarbonisation [1]. Even if electrified railway vehicles have been deployed for many decades, diesel topologies remain the preferred option in many railway networks. This trend is specially noticeable in track sections where the electrification is barely cost-effective, for instance in low-traffic networks [2]. In this context, the interest of the railway industry on integrating new technologies such as Lithium-ion Batteries (LIB) or Hydrogen Fuel Cells (FC) has increased in recent years. Railway vehicles solely powered by LIBs are found to be more appropriate for short and low-demanding routes [3], considering the space and weight limitations that hinder the integration of big and heavy batteries. Besides, railway vehicles powered by FCs are found to be a feasible solution for longer ranges, owing to the higher energy density and faster refuelling of this technology [4]. However, the high price of the hydrogen makes this option roughly competitive, at least in the short-term [5].

In this regard, hybrid vehicles combining a diesel generator (genset) and a LIB emerge as an alternative solution to reduce the pollutant emissions of non-electrified long railway lines in the short and mid-term. Previous studies have highlighted that increasing the battery use reduces the Life Cycle Cost (LCC) of this vehicle topology [6]. An option to enhance the use of the LIB is to enlarge its size (i.e. to increase the hybridization level). However, it is also possible to increase the charging frequency by deploying Opportunity Charging Points (OCP) along the route. This option allows to maintain the hybridization level and reduce the size of the LIB. However, it can involve a reduction on the LIB life (increased number of cycles) or a higher investment on infrastructure (to install OCPs). Previous studies have analysed the economic suitability of this approach, but focused on short routes [7]–[9] or hydrogen-based topologies [10]. Therefore, a lack of studies dealing with the cost-efficiency of OCPs in long-distance railway lines driven by hybrid diesel vehicles is identified.

Therefore, the aim of this paper is to analyse the LCC of OCPs deployment in long non-electrified railway lines. A study case based on a real line driven by a hybrid railway vehicle is presented, where potential locations for the OCPs are proposed and techno-economically analysed. Considering that the defined Energy Management Strategy (EMS), LIB technology and size of the powertrain elements (LIB and genset) affect the LCC of this railway topology [6], these aspects are also considered in the developed analysis. Indeed, for each potential combination of OCP locations, two EMSs and two LIB technologies are compared, and for each case the optimal genset and LIB sizes are calculated. The paper is organised as follows. Section II shows the analysed scenario. Section III introduces the analysed OCP locations, LIB technologies and EMSs. The methodology for the LCC calculation is presented in Sections IV-V. In Section VI the obtained results are discussed, and the main conclusions are reviewed in Section VII.

II. SCENARIO OVERVIEW

This study is focused on the railway topology denoted as bi-mode battery-based Hybrid Diesel-Electric Multiple Unit (H-DEMU). A H-DEMU can be powered by a genset, a LIB

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or a catenary (as in a OCP), as shown in Fig. 1. The figure also highlights the difference between the H-DEMU and a traditional Diesel-Electric Multiple Unit (DEMU). Besides, the driving scenario proposed in this study is based on the ”Monforte de Lemos - A Coruña” railway line (Spain). The round trip route is composed of 378.8 km and is completed in 4 hours. Fig. 2 shows the corresponding speed profile.

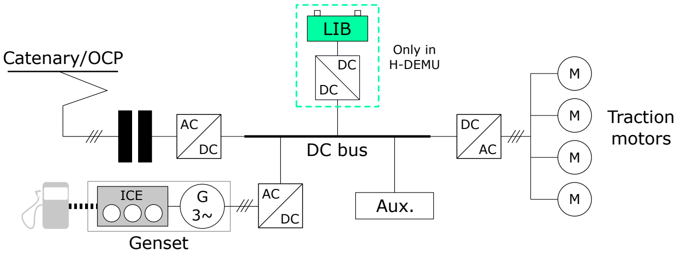


Fig. 1. H-DEMU and DEMU architectures (with and without LIB).

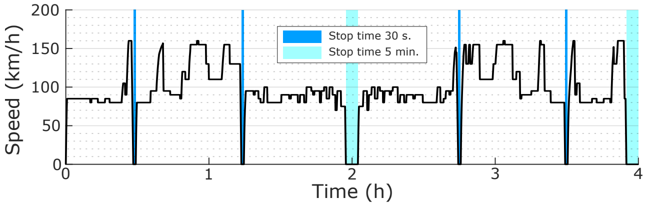


Fig. 2. Speed profile of ”Monforte de Lemos - A Coruña” line.

III. Overview of sensitivity analysis

In this study, different potential locations for the OCPs are analysed. For each combination of locations, two LIB technologies and two EMSs are also considered.

A. OCPs location

As shown in Fig. 2, the train stops in 6 stations along the route. However, only in two cases (middle and terminal stations) the stop time is higher than 30 seconds. Considering that the obtained charge in less than one minute is residual (see Section III-B for the charging rates of nowadays LIB technologies), only the middle and terminal stations can be considered as potential OCPs. Consequently, three combinations of OCPs are considered in the current study: no charging, charging in terminal station, and charging in both middle and terminal stations. These cases will be denoted as Case ○○, Case ○● and Case ●●, respectively (○ represents a non-charging and ● a charging station). Even if some differences can be denoted, it is considered that from a macroscopic energetic point of view Case ●○ is very similar to Case ○●. Hence, in this study Case ●○ is not addressed.

B. LIB Technologies

Depending on the deployed anode and cathode material, different LIB technologies exist [11]. In the current study two chemistries are considered, which were regarded as the most promising ones in similar applications [6] (cathode/anode): Lithium Nickel Manganese Cobalt Oxide/Graphite and Lithium Nickel Manganese Cobalt/Titanate. In the remainder they will be denoted as NMC and LTO, respectively. They differ in terms such as nominal voltage, charge and discharge rate, life, specific energy, energy density and cost (Table I).

TABLE I
Parameters of considered LIB chemistries (cell level)

	NMC	LTO
Nominal voltage [V]	3.7	2.3
Max. C-rate (charge/discharge) [C]	3.0 / 5.0	4.0 / 4.5
Calendar Life [years]	15	20
Cycle Life (@80%DOD) [cycles]	3,300	28,800
Specific Energy (pack level) [Wh/kg]	86.9	53.3
Energy Density (pack level) [Wh/L]	122.2	52.8

C. Energy Management Strategies

The proposed strategies are in charge of dividing the power demand between the genset and LIB. The EMSs analysed in this paper were defined as the most promising ones for similar applications in a previous study [6], and are introduced below.

1) Optimized State Machine (GA-SM): This strategy is based on a set of rules. In short, depending on the State of Charge (SOC) of the LIB and the instantaneous demand (P_{dem}), a different reference is set for the genset power (P_{gen}). Then, the difference between P_{dem} and P_{gen} is given or absorbed by the LIB (P_{LIB}). First, three states are defined depending on the SOC of the LIB (see Fig. 3): high SOC, middle SOC and low SOC. At each state, a different set of rules is designed to define P_{gen}, as it is shown in Fig. 4. The rules were defined considering the efficiency map of the genset (Fig. 5), specifically the operation points P_{gen1} (low limit of middle efficiency zone), P_{gen2} (low limit of high efficiency zone) and $P_{gen-max}$ (maximum load). In low SOC state (Fig. 4a), the genset always works at $P_{gen-max}$ to recover as fast as possible the SOC of the LIB. The middle SOC state strategy (Fig. 4b) is defined adding an additional rule to the strategy of low SOC: when the demand is lower than $P_{gen-max}$, the genset reference is reduced to P_{gen2}. Finally, the high SOC state strategy (Fig. 4c) is also defined adding an additional rule to the strategy of middle SOC: when the demand is lower than P_{gen2}, the genset reference is fixed at P_{gen1}. In all cases, P_{gen} is reduced when the LIB cannot be further charged, but it never falls bellow P_{gen1}. A key design step of this strategy is the definition of the thresholds SOC_1-SOC_4 (Fig. 3). These values are optimised by means of a Genetic Algorithm (GA) approach, in order to adapt as best as possible their values to the scenario being analysed (see Section IV).

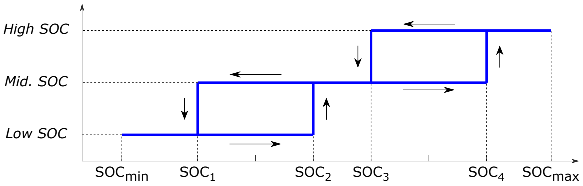


Fig. 3. States of State Machine Strategy.

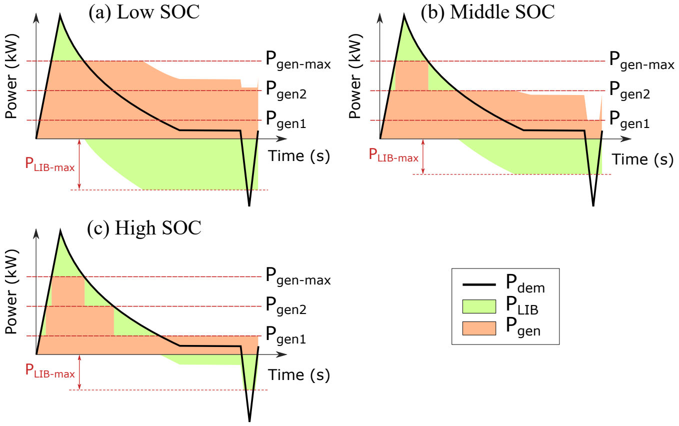
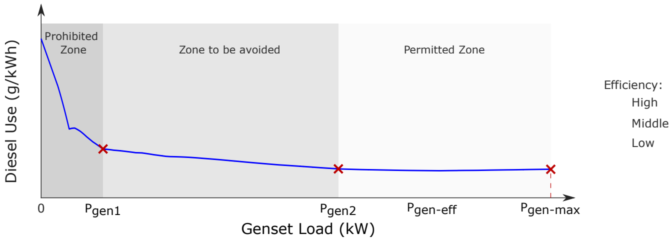


Fig. 4. Rules in SM strategy: a) Low SOC b) Mid. SOC c) High SOC.



B. Optimization by Exhaustive Search (DP strategy)

The optimization by exhaustive search consists on an iterative sequence composed of four steps, in which all the range of feasible solutions ($j \in j_{max}$) is assessed. The main steps are depicted in Fig. 8 and further detailed in Section V.

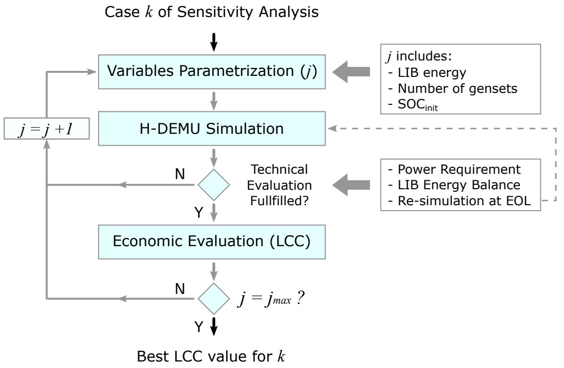


Fig. 8. Diagram for optimization by exhaustive search.

V. METHODOLOGY FOR LCC CALCULATION

In this section, the main steps of the optimization methodologies presented in Section IV (Figs. 7 and 8) are introduced together, since they are common in both approaches.

A. Variables/Individuals Parametrization

Table II defines the bounds of the variables that compose j and i (SOC_1-SOC_4 are given as a single variable SOC_x). N_{LB} and N_{GS} define the maximum number of LIB modules and gensets, respectively. Each LIB module is constructed connecting cells in series and parallel to reach a nominal energy of 20 kWh, and each genset has a nominal power of 500kW. Due to space limitations, N_{LB} changes with respect to N_{GS} (i.e. if more gensets are integrated, less space is available for the LIB). N_{LB} also varies with respect to the LIB technology, as the energy densities differ (Table I). It is worth to point out that SOC_{ini} is a continuous variable in the GA approach and an integer variable in the exhaustive search.

TABLE II
OPTIMIZATION VARIABLES AND BOUNDS

Variable		Bounds		Optimization Approach
$n_{LB}(j/i)$	$\in$	$\{1, 2, \dots N_{LB}\}$	[-]	Exhaustive Search, GA
$n_{GS}(j/i)$	$\in$	$\{1, 2, \dots N_{GS}\}$	[-]	Exhaustive Search, GA
$SOC_{ini}(j/i)$	$\in$	$\{20 - 90\}$	[%]	Exhaustive Search, GA
$SOC_x(j/i)$	$\in$	$\{20 - 90\}$	[%]	GA (in GA-SM strategy)

B. H-DEMU Simulation and Technical Evaluation

The performance of the H-DEMU is evaluated by means of a quasi-static simulation model developed in MATLAB. For further information regarding the model, see [3] and [6]. At this step, LIB characteristics (capacity and internal resistance) are set at Beginning-of-Life (BOL) values.

Then, simulation results are technically evaluated considering the aspects of power requirement and LIB energy balance [6]. Afterwards, the simulation is repeated with LIB characteristics set at End-of-Life (EOL) values. Iteration j or individual i is considered feasible and its LCC is calculated only if the technical aspects are met in both simulations (BOL and EOL).

C. Economic Evaluation (LCC Model)

The cost model returns the LCC value of each feasible solution, which corresponds to the minimization function of both optimization approaches. The model considers the costs of the whole H-DEMU lifetime, divided into acquisition (C_{acq}), operation (C_{op}) and maintenance costs (C_{maint}).

$$LCC(i/j) = C_{acq}(i/j) + C_{op}(i/j) + C_{maint} \tag{2}$$

1) Acquisition Cost: C_{acq} includes the initial costs of the LIB, genset, OCPs deployment and the rest of the train.

$$\begin{aligned} C_{acq}(i/j) = C_{tr} + \frac{c_{ocp} \cdot n_{ocp}(i/j)}{n_{tr}} + \\ + c_{LB} \cdot n_{LB}(i/j) + c_{GS} \cdot n_{GS}(i/j) \end{aligned} \tag{3}$$

being C_{tr} the cost of the train without LIB and genset, c_{ocp} the cost of a single OCP, n_{ocp} the number of deployed OCPs, n_{tr} the number of trains running in the line, c_{LB} the referential cost of the LIB, and c_{GS} the referencial cost of a genset.

2) Operation Cost: C_{op} includes the costs related to the daily diesel and electricity use (C_{day}) and to the required LIB replacements (C_{repl}):

$$C_{op}(i/j) = C_{day}(i/j) + C_{repl}(i/j) \tag{4}$$

On the one hand, C_{day} is calculated annualizing the daily fuel and electricity consumptions:

$$C_{day}(i/j) = \sum_{y=1}^{Y} \left(L_f(i/j) \cdot c_f + E_{el}(i/j) \cdot c_{el}\right) \cdot t_{op} \cdot (1+I)^{-y} \tag{5}$$

being L_f the daily fuel consumption, c_f the referential fuel cost, E_{el} the daily electricity consumption, c_{el} the referential electricity cost, t_{op} the operation days per year, I the discount rate, y the current year, and Y the service life.

On the other hand, C_{repl} is obtained as follows, where R is the number of replacements, y_{LB} is the estimated LIB lifetime, and r is the current replacement:

$$C_{repl}(i/j) = \sum_{r=1}^{R(i/j)} c_{LB} \cdot n_{LB}(i/j) \cdot (1 + I)^{-r \cdot y_{LB}(i/j)} \tag{6}$$

The LIB life estimation is obtained by an empirical degradation model developed by the authors in [11]. The model considers the differences between LIB technologies, and parametrizes the effect of the temperature (T), depth-of-discharge (DOD), charge and discharge currents (C_{ch} and C_{dch}) and middle SOC ($mSOC$), as Eq. (7) shows.

$$y_{LB}(i/j) = f(T, DOD, C_{ch}, C_{dch}, mSOC) \tag{7}$$

3) Maintenance Cost: C_{maint} includes the costs related to the maintenance of the H-DEMU. An average value for the cost per year is defined (c_{maint}), which is then annualized.

$$C_{maint} = \sum_{y=1}^{Y} c_{maint} \cdot (1+I)^{-y} \tag{8}$$

VI. RESULTS AND DISCUSSION

After introducing the use case and the proposed methodology for the LCC optimization, in this section the results of the sensitivity analysis are presented. Moreover, a techno-economic discussion is developed focusing on the cost-efficiency of the OCPs. Table III shows the considered economic parameters, which are defined according to the values typically given in the literature. The analysis of this section is divided into two case studies. In the base case, it is assumed that the stations were already electrified, and hence c_{ocp} becomes zero. Then, in the extended case it is assumed that electrification is required, so c_{ocp} is defined as in Table III. Besides, as the cost-efficiency of the OCPs is also affected by the number of trains using these facilities (n_{tr}), the sensitivity to that value is also analysed in this case study.

TABLE III
ECONOMIC PARAMETERS

Parameter	Value	Parameter	Value
t_{op} [days/year]	320	c_{LB} [€/kWh]	800 - 1,500
T [years]	30	c_{GS} [€/kW]	500
I [%]	2.5	c_f [€/kg]	1.1
c_{ocp} [€/kWh]	600,000	c_{el} [€/kWh]	0.06

A. Base Case Study: no cost for OCPs deployment

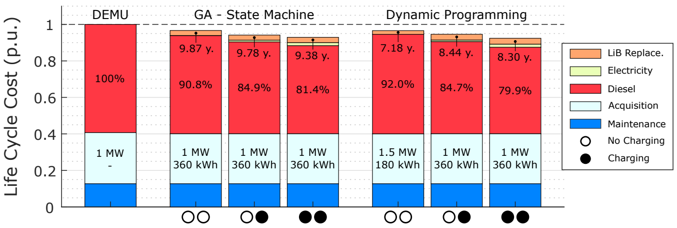
Table IV shows the LCC value of each case of the analysis, which is given in p.u. values in relation to the results of a traditional DEMU. The results are extended in Fig. 9, where the LCC is split into the terms of Eqs. (2) and (4). The figure also gives the values n_{LB} (kWh), n_{GS} (MW), L_f (% of a DEMU) and y_{LB} (years) for each case of the analysis.

TABLE IV
SUMMARY OF BASE CASE RESULTS (LCC VALUES)

LIB	EMS	Case ○○	Case ○●	Case ●●
LTO	*GA - State Machine*	0.967	0.941	0.929
	Dynamic Programming	0.966	0.946	0.924
NMC	*GA - State Machine*	0.970	0.950	0.940
	Dynamic Programming	0.971	0.953	0.929

The results demonstrate that, at least when electrified stations are available, deploying OCPs along the route is an interesting option from an economic scope. With an appropriate EMS (GA-SM and DP strategies), Cases ○● and ●● obtain a lower LCC compared to both the traditional DEMU and the case without OCPs (Case ○○). In the best scenario (LTO technology, DP strategy and Case ●●), the LCC is reduced a 7.6% compared to the DEMU, and a 4.3% compared to Case ○○. There are two main reasons that make the OCPs be cost-effective. On the one hand, the cost of the LIB degradation does not increase a lot when raising the charging frequency (see y_{LB} values in Fig. 9). On the other hand, the diesel use is clearly reduced when the LIB is charged along the route, and as the required electricity for the charging involves a lower cost, the final LCC is inevitably reduced. Due to the same reasons, the results in Case ●● are always better than in Case ○●. Fig. 10a shows an example of the SOC evolution comparison between Cases ○○, ○● and ●●.

(a) LTO



(b) NMC

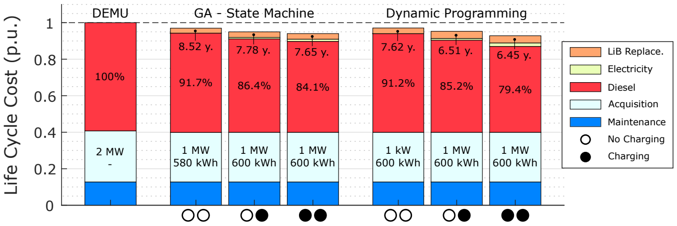


Fig. 9. Extended base case results: a) LTO b) NMC. From up to down, values represent : y_{LB} (years), L_f (% of a DEMU), n_{GS} (MW) and n_{LB} (kWh).

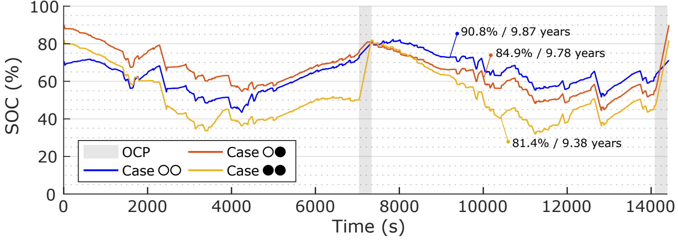
Regarding the comparison of the different EMSs, GA-SM obtains results close to the global optimization proposed by DP, what validates its effectiveness as a strategy. With the same LIB and genset sizes, the fuel use obtained by DP strategy is always lower (in fact, it is not possible to improve it, as DP returns the control sequence that reduces most the diesel use). However, being the fuel use the only optimization variable, the proposed strategy does not always ensure an appropriate control of the LIB degradation. Due to this reason, in some cases a lower LCC is obtained with GA-SM strategy. Fig. 10b shows a representative case to compare both strategies: DP obtains a lower fuel consumption, but reducing the LIB life.

Finally, the comparison of the LIB technologies shows that there is not much difference between NMC and LTO. In fact, they do not differ more than a 1.2%. Anyway, LTO obtains always a slightly better result due to the lower diesel consumption value. Even if NMC allows integrating more energy, it cannot exploit it as much as LTO, since its charging speed is lower and it degrades more at high DODs (see Table I). This issue can be checked in the example given in Fig. 10c.

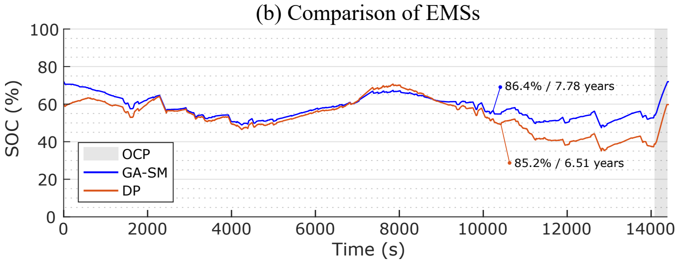
B. Extended Case Study: sensitivity to number of H-DEMUs

In the extended case study, the acquisition cost of deploying OCPs (c_{ocp}) is also considered in the analysis. All the results obtained in the previous subsection are also valid in this extended case, the only difference is that the term C_{ocp} is added to the LCC value. Table V shows the number of trains (n_{tr}) that are required in each case of the sensitivity analysis to maintain the cost-efficiency of the OCPs in this new scenario.

(a) Comparison of OCP locations



(b) Comparison of EMSs



(c) Comparison of LIB technologies

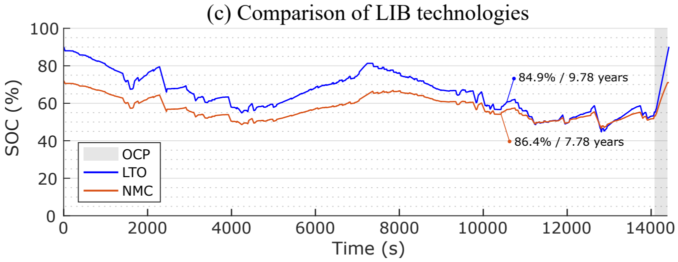


Fig. 10. Simulation results (SOC evolution) of representative cases: a) LTO, GA-SM b) NMC, Case ○● c) GA-SM, Case ○●. Numeric points represent L_f (% of a DEMU) and y_{LB} (years), respectively.

The results show that in most of the cases deploying charging activities along the route is cost-effective even in the worst case, i.e. when only one H-DEMU is driving in the line. Another fact to highlight is that when considering the installation cost of the OCPs, the difference between Cases ○● and ●● is almost residual. This proves that the main benefit comes when installing just one OCP, as adding more OCPs does not always improve the obtained LCC. In the cases when the exact number of trains driving in the line is known, an exhaustive analysis focused on the cost-efficiency of this cases in relation to the DEMU and Case ○○ can be developed.

TABLE V
REQUIRED H-DEMUS TO MAKE OCPS BE COST-EFFECTIVE

LIB	**EMS**	**Case ○●**	**Case ●●**
LTO	*GA - State Machine*	1	1
	Dynamic Programming	1	1
NMC	*GA - State Machine*	1	2
	Dynamic Programming	2	1

VII. CONCLUSIONS

This paper has presented a LCC analysis for railway projects involving H-DEMUs, focused on the cost-efficiency of deploying OCPs along the route. As they are considered to be important aspects to reduce the LCC, the proposed analysis has also considered the effects of the selected EMS, LIB technology, and LIB and genset sizes. A methodology for developing the proposed analysis has been introduced, which has been implemented in a real railway line-based scenario.

The results have demonstrated that deploying OCPs along the route is a cost-effective option in scenarios similar to the one proposed in this paper, at least if appropriate EMSs (e.g. GA-PF) and LIB technologies (e.g. LTO) are selected. When the infrastructure of the OCPs is already constructed, a lower LCC is obtained as more charging activities are proposed. However, when the electrification cost has to be considered, there is no need to deploy more OCPs than the one in the terminal station.

Future developments may propose an extension of the LCC analysis in order to evaluate the effect of different economic parameters or driving scenarios on the obtained conclusions.

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