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In-depth Life Cycle Cost Analysis of a Li-ion Battery-based Hybrid Diesel-Electric Multiple Unit

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***Abstract*—This study analyzes the life cycle costs of railway projects involving hybrid diesel-electric multiple units, focusing on the influence of lithium-ion battery technologies and energy management strategies. Specifically, 3 lithium-ion battery technologies and 6 energy management strategies are proposed, leading to a sensitivity analysis composed of 18 cases. In addition, for each case an approach for the optimal sizing of the diesel generator and lithium-ion battery is proposed. A scenario based on a real railway line is introduced and the results are compared to a traditional diesel-electric multiple unit. Potential life cycle cost savings of 16.0% are obtained when deploying a global optimization-based energy management strategy and LTO batteries.**

***Index Terms*—Energy management strategy, life cycle cost analysis, lithium-ion battery, railway.**

I. Introduction

Diesel powered vehicles remain the preferred option in many railway systems, especially in track sections where the electrification is barely cost-efficient. For instance, in Europe the 40% of the routes are not electrified yet [1]. In this context, the interest of the railway industry on integrating Energy Storage Systems (ESS) has increased in the last years due to recent developments on these technologies, particularly on Lithium-ion Batteries (LIBs) and Fuel Cells (FCs). Given that railway vehicles solely powered by LIBs or FCs are roughly cost-effective compared to their diesel counterpart [2], hybrid vehicles combining different energy sources emerge as an alternative solution for the short and mid-term future.

Some publications have recently approached the cost-efficiency of hybrid diesel railway vehicles. A clear example is given in [3], where the cost of a hybrid vehicle is found to be 15% lower than in a traditional diesel powered train. Different ESS technologies are proposed to compare their performance – LIBs, Electric Double Layer Capacitors and Flywheels. The results show that integrating LIBs is the best solution. Besides, the authors in [4] found that a correctly sized hybrid diesel locomotive can reduce the final cost a 14% compared to a traditional diesel locomotive. Finally, in [5] a hybrid train is compared to a traditional diesel vehicle in economic terms. Different architectures and ESS sizings are proposed for the hybrid alternative. The results show that a payback time of 2 years can be obtained with these topologies.

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When dealing with hybrid vehicles, the definition of the power split ratio between the different power sources has a strong impact on the lifetime costs [6]. As this is one of its main tasks, the relevance of the Energy Management Strategy (EMS) can not be dismissed. In addition, the influence of the selected ESS technology can neither be ignored, either in technical or economical terms. However, neither of the studies previously mentioned on the state-of-art review approaches the question of how the selected EMS and LIB technology influences the final cost of the system.

In this regard, the aim of the current study is to analyze the influence of different EMSs and LIB technologies on the Life Cycle Costs (LCC) of railway projects. Specifically, the study is focused on the railway topology denoted as battery-based Hybrid Diesel-Electric Multiple Unit (H-DEMU), which can be powered by a catenary, a diesel generator (genset) or a LIB. Fig. 1 shows the difference between a battery-based H-DEMU and a traditional Diesel-Electric Multiple Unit (DEMU).

The remainder of the paper is organized as follows. First, the scenario used to develop the LCC analysis is presented in Section II. Section III introduces the proposed EMSs and LIB technologies, which constitute the cases to be analized. Then, Section IV presents the approach for the LCC calculation, including an optimization that returns the cost-optimal LIB and genset sizing for each case of the sensitivity analysis. Finally, the results are presented and techno-economically evaluated in Section V.

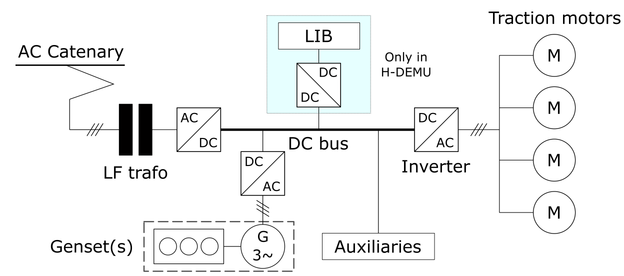

Fig. 1. H-DEMU and DEMU architectures (with and without LIB).

II. Scenario Overview

The scenario proposed for this study is based on the "St Pancras - Nottingham" railway line (UK). The round trip route is composed of 470 km. Fig. 2 shows the speed profile, where two driving modes are differentiated. The first mode combines catenary and LIB operation – the catenary provides traction power, and when required the LIB is charged in order to complete the route in an acceptable State-of-Charge (SOC). The second driving mode combines diesel and LIB operation. For this mode, different EMSs are proposed in Section III.

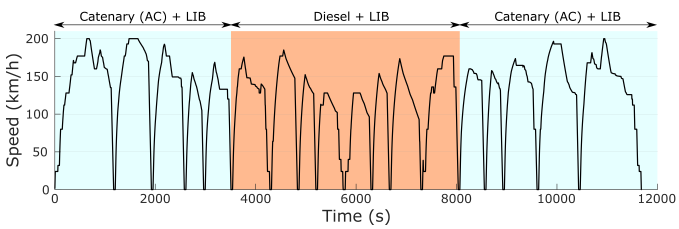

Fig. 2. Speed profile of "St Pancras - Nottingham" line.

III. Sensitivity Analysis Overview

In this study 18 cases are proposed in the sensitivity analysis, which combine 3 LIB technologies and 6 EMSs.

A. LIB Technologies

Different LIB technologies exist depending on the deployed anode and cathode material. In the current study the following chemistries are considered (cathode/anode): Lithium Iron Phosphate/Graphite (LFP/G), Lithium Nickel Manganese Cobalt Oxide/Graphite (NMC/G) and Lithium NMC/Titanate (NMC/LTO). For the sake of simplicity, in the remainder these technologies will be referred as LFP, NMC and LTO, respectively. These chemistries differ in terms such as voltage, cost, lifetime or specific energy, as Table I outlines.

TABLE I
Parameters of considered LIB chemistries (cell level)

	LFP/G	**NMC/G**	**NMC/LTO**
Nominal voltage [V]	3.2	3.7	2.3
Max. C-rate (charge/discharge) [C]	4.0 / 6.5	3.0 / 5.0	4.0 / 4.5
Calendar Life [years]	10	15	20
Cycle Life (@80%DOD) [cycles]	4,400	4,800	24,200
Specific Energy (pack level) [Wh/kg]	48.0	86.9	53.3

B. Energy Management Strategies

EMSs for hybrid vehicles are typically divided into rule-based (deterministic and fuzzy) and optimization-based (global and real-time) strategies [7]. In the present paper 5 deterministic rule-based (D-RB) strategies and one global optimization (G-OP) strategy are proposed. Since the G-OP strategy is hardly applicable in real operation, in the current study it is just used as baseline for evaluating the proposed D-RB strategies.

1) D-RB – Genset Follower (GF): In this approach a constant power reference is defined for the genset, allowing a high efficiency genset operation. Consequently, the LIB works as a buffer, giving or receiving power depending on the difference between the genset reference and the instantaneous demand (Fig. 3a). The genset works at maximum load only if the LIB cannot provide the required power peak.

2) D-RB – Improved Genset Follower (IGF): This approach is based on the GF strategy. However, it extends the genset operation to more points, considering the associated efficiency (Fig. 4). In short, the genset is adapted to the power demand, but it is forced to work on its high efficiency zone, as Fig. 3b shows. It is only allowed to leave this zone in order to avoid overcharging the LIB.

3) D-RB – Demand Follower (DF): In this strategy, as in GF, a constant power reference is set for the genset. However, in this case, when the demand is lower than the genset reference, the LIB does not absorb power and the genset set point is reduced to "follow" the demand (Fig. 3c). Hence, the LIB is only charged with the energy recovered from braking.

4) D-RB – Improved Demand Follower (IDF): This approach combines the features of IGF and DF. Typically, the genset is allowed to work on its high efficiency zone (Fig. 4), but when the demand is lower than the P_gen_2 threshold, the genset reference is reduced to "follow" the demand (Fig. 3d).

5) D-RB – State Machine (SM): In this strategy, three different states are defined depending on the LIB SOC: High SOC, Middle SOC and Low SOC (Fig. 5). At each state, a different strategy is adopted. In High SOC state the objective is to reduce the use of the genset, and therefore the IDF strategy is adopted. In Middle SOC, the IGF strategy is adopted, so the LIB can be sometimes charged from the genset. Finally, in Low SOC state, the genset always works at maximum load in order to charge the LIB.

6) G-OP – Dynamic Programing (DP): This G-OP approach is based on an algorithm that calculates the optimal split factor (in terms of fuel consumption) between the genset and LIB for each time step based on Bellman's optimality principle. The resulting operation is characterized by frequent switches in the power split factor, so DP is commonly used just as baseline for benchmarking new EMSs or for off-line optimization [7]. The optimization problem is based on the following cost function:

$$J = \sum_{n=0}^{N-1} \Delta m f_{ICE}(U(n)) \cdot T_s \tag{1}$$

where $\Delta m f_{ICE} \cdot T_s$ refers to the fuel mass consumption at each time step, determined by the power split factor U, within the route length N. The DP algorithm integrated in the current study is based on the function developed by [8].

IV. LCC Calculation Approach

An overview of the proposed LCC calculation approach is depicted in Fig. 6. The aim is to obtain the LCC of each case to be analyzed in the sensitivity analysis ($k \in k_{max}$). When evaluating each case k, an optimization approach is set in order to define the cost-optimal combination of installed LIB energy (e_{LIB}) and number of gensets (n_{gen}). The optimization is an iterative sequence with four steps – variables parametrization, H-DEMU simulation, technical evaluation and economic

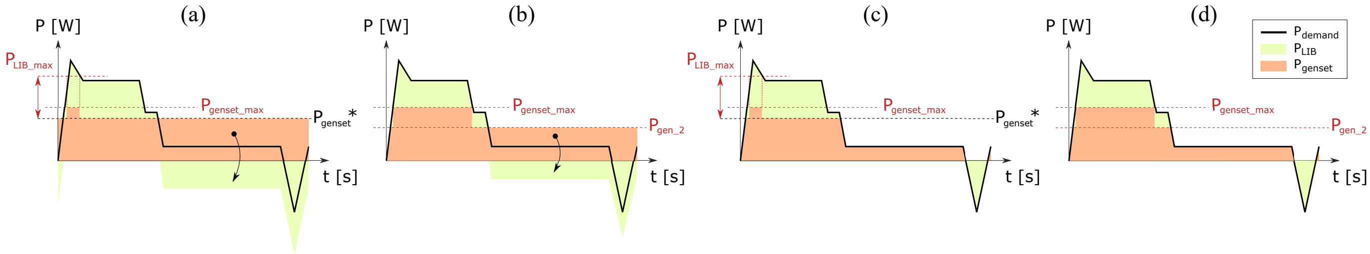

Fig. 3. Rule-based Strategies: a) Genset Follower b) Improved Genset Follower c) Demand Follower d) Improved Demand Follower

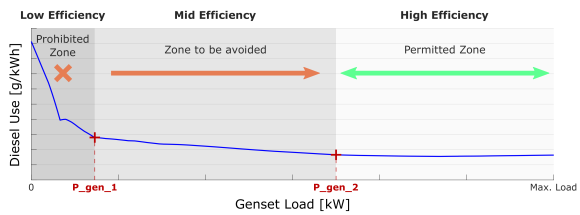

Fig. 4. Diesel generator consumption vs. demanded load.

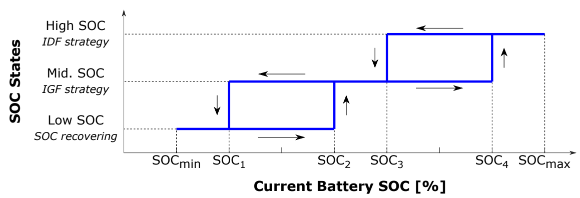

Fig. 5. Definition of states for State Machine controller.

evaluation. At each iteration i a set of feasible solutions is evaluated, until the range of solutions i_{max} is completely assessed.

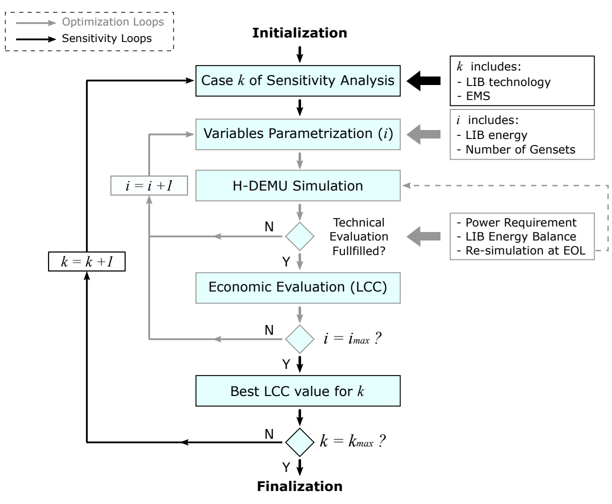

Fig. 6. LCC Calculation Approach.

A. Variables Parametrization

In the first step, the set of variables to be evaluated is defined. The bounds of the variables are defined as follows:

$$e_{LIB}(i) \in e_{br} \cdot \{1, 2, ... N_{br}\} \quad (2)$$

$$n_{gen}(i) \in \{1, 2, ... N_{gen}\} \quad (3)$$

being e_{br} the energy of one LIB branch (which is constructed connecting LIB cells in series and parallel), N_{br} the maximum number of LIB branches connected in parallel, and N_{gen} the maximum number of gensets integrated in the vehicle.

B. H-DEMU Simulation Model

The performance of the H-DEMU is evaluated by means of a simulation model developed in MATLAB. The model is of quasi-static nature, and calculates the power consumed by the vehicle at each discrete step ($\Delta t = 1s$) following a predefined driving profile (Fig. 2) by going upstream through the vehicle components (Fig. 1, modeled as in [6]). At this step, LIB characteristics (capacity and internal resistance) are set at Beginning-of-Life (BOL) values.

C. Technical Evaluation

The simulation results are technically evaluated considering the aspects of power requirement (the demand must be fulfilled at each discrete step Δt) and energy balance (the LIB must start the second round trip in the same or higher SOC). Then, the simulation is repeated with the LIB characteristics set at End-of-Life (EOL) values. Iteration i is considered feasible and its LCC is calculated only if the technical aspects are met in both simulations. Then, the LCC is calculated with the results of the first simulation (LIB characteristics set at BOL).

D. Economic Evaluation (LCC Model)

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

$$LCC(i) = C_{acq} + C_{op} + C_{maint} \quad (4)$$

1) Acquisition Cost: This term includes the initial cost of the LIB, genset and the rest of the train.

$$C_{acq} = C_{train} + c_{LIB} \cdot e_{LIB}(i) + c_{gen} \cdot n_{gen}(i) \quad (5)$$

where C_{train} refers to the cost of the train without LIB and genset, c_{LIB} to the referential cost per kWh of the LIB technology, and c_{gen} to the referential cost of a single genset.

2) Operation Cost: The second term includes the costs related to the daily operation (diesel and electricity consumption) and to the operation of the LIB (required replacements):

$$C_{op} = C_{daily} + C_{overhaul} \tag{6}$$

being C_{daily} the cost related to the daily operation, and $C_{overhaul}$ the cost related to the LIB replacements.

The daily cost is calculated as the aggregation of the diesel and electricity consumption, and then the value is annualized.

$$C_{daily} = \sum_{y=1}^{T} (L_f(i) \cdot c_f + E_{cat}(i) \cdot c_{cat}) \cdot t_{op} \cdot (1+I)^{-y} \tag{7}$$

where $L_f(i)$ is the daily diesel consumption, c_f the referential fuel cost, $E_{cat}(i)$ the daily electricity consumption, c_{cat} the referential electricity cost, t_{op} the operation days per year, I the discount rate, y the current year, and T the service life.

On the other hand, the cost related to the LIB replacements is obtained as follows:

$$C_{overhaul} = \sum_{r=1}^{R_{LIB}} c_{LIB} \cdot e_{LIB}(i) \cdot (1+I)^{-r \cdot y_{LIB}} \tag{8}$$

being R_{LIB} the total LIB replacements, y_{LIB} the estimated LIB lifetime, and r the number of the current LIB replacement.

The lifespan estimation is obtained by the Wöhler Curve method [6]. The Wöhler curve defines the amount of charge and discharge cycles that each LIB technology can withstand at each Depth-of-Discharge (DOD) before reaching the EOL. In the current approach, the DOD impact from [9] is used to model the lifetime of each LIB chemistry. The lifespan expression stands as follows:

$$Life_{BT} = \Big(\sum_{j=1}^{n_{DOD}} n_{dj}(i) \cdot t_{OP} \cdot {CF_{uj}}^{-1} \Big)^{-1} \tag{9}$$

where n_{DOD} denotes the number of different DOD ranges, $n_{dj}(i)$ the cycles counted per day at each DOD range j, and CF_{uj} the maximum cycles allowed at each range.

3) Maintenance Cost: This term includes the costs related to the maintenance of the H-DEMU elements. An average value for the cost per year is defined, which is then annualized.

$$C_{maint} = \sum_{y=1}^{T} c_{maint} \cdot (1+I)^{-y} \tag{10}$$

being c_{maint} the average maintenance cost in a year.

V. Results and Discussion

In this section the results of the sensitivity analysis are presented and evaluated for the scenario proposed in Section II. Regarding the optimization bounds, e_{br} is defined as 50 kWh, N_{br} as 40 branches, and N_{gen} as 5 gensets.

Fig. 7 shows the LCC of each proposed case, divided into the terms of Eq. (2). Additionally, operation costs are divided into diesel, catenery and overhaul costs. The results are extended in Table II with the optimal sizing values (e_{LIB} and n_{gen}), LCC, diesel consumption (L_f) and number of LIB replacements (R_{LIB}). LCC and L_f are given in per unit (p.u.) values in relation to the results of a DEMU, and the most relevant values are highlighted.

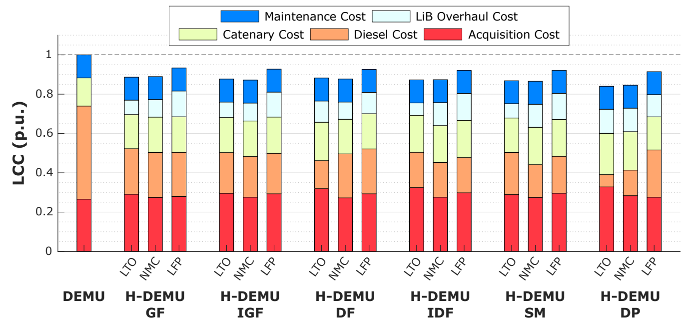

Fig. 7. LCC Results for the different EMS and LIB technologies.

TABLE II
Summary of Results

EMS	LIB	e_LIB [kWh]	n_gen [-]	LCC [p.u.]	L_f [p.u.]	R_LIB [-]
DEMU	-	-	5	1	1	-
	LTO	1200	1	**0.886**	0.487	2
GF	NMC	1900	1	0.889	0.483	3
	LFP	1400	1	0.933	0.474	4
	LTO	1300	1	0.877	0.435	2
IGF	NMC	1950	1	**0.872**	0.435	3
	LFP	1800	1	0.927	0.436	3
	LTO	1800	1	0.882	**0.297**	2
DF	NMC	1400	2	**0.877**	0.473	4
	LFP	1550	2	0.926	0.482	3
	LTO	1900	1	**0.873**	0.377	1
IDF	NMC	1950	1	0.874	0.373	4
	LFP	1950	1	0.920	0.377	3
	LTO	1150	1	0.868	0.453	2
SM	NMC	1900	1	**0.866**	0.355	4
	LFP	1900	1	0.921	0.396	3
	LTO	1950	1	**0.840**	**0.131**	2
DP	NMC	1900	2	0.846	0.276	4
	LFP	1650	2	0.911	0.319	4

A. Analysis of Optimal Sizing Results

The analysis of the sizing results indicates that deploying a single genset is the optimal alternative for the D-RB strategies, except in two cases where it is not feasible (DF strategy with NMC and LFP technologies). A higher installed LIB energy than the allowed one would be necessary to deploy a single genset in these cases. However, regarding the G-OP strategy, only in the case of LTO is a single genset the optimal solution. Therefore, it is demonstrated that deploying a single genset is not the cost-optimal solution in all the cases.

Regarding the installed energy, the optimal values are always higher than 1 MWh. GF and IGF require in general less installed energy than DF and IDF (except in the cases with 2 gensets). Indeed, in GF and IGF the LIB can recover energy from the genset, and therefore less capacity is necessary. In SM strategy, values close to the ones of GF and IGF are obtained. Focusing on the different chemistries, if the cases with the same number of gensets are compared, LTO requires less installed energy. The main reason is that LTO technology allows higher DODs, as this does not reduce its lifetime as it does in NMC and LFP.

B. Analysis of EMSs

The first conclusion when focusing on the results of the strategies is that in all the cases the LCC of the traditional DEMU is reduced. Therefore, the economic feasibility of the H-DEMU topology is demonstrated in the current scenario.

DP strategy obtains the best results for all the chemistries, reaching a maximum LCC reduction of the 16.0% compared to the DEMU. It is also the strategy showing a lowest diesel use, with a maximum reduction of the 86.9%. However, as it was mentioned in Section III, DP is hardly applicable in real operation. Therefore, these results are used to evaluate the D-RB strategies.

The D-RB strategy with the best overall performance is found to be SM, what demonstrates the potential of combining different strategies. When integrating NMC and LTO, SM obtains the best results, and with LFP it is just 0.1% ahead of the best result (IDF). Compared to DP, it shows LCC values 2.8% (LTO), 2.0% (NMC) and 0.9% (LFP) higher, while the LCC of the DEMU is reduced a 13.2%, 13.4% and 8.0%, respectively. Therefore, even if SM does not outperform the G-OP strategy, LCC values are lower than in a typical DEMU.

Another feature of the D-RB strategies is that they all obtain similar results. GF shows the poorest performance with all the chemistries, but the difference to SM is around 1.2-2.3%, a low value compared to the reduction obtained against the DEMU. As mentioned in Section III, IGF and IDF were designed as improvements of GF and DF, respectively. The results show that both strategies reduce the LCC of their respective original strategy (0.6-1.7% in IPF and 0.3-0.9% in IDF). In addition, the general trend shows that IDF shows better results than IGF, as well as DF outperforms GF. Therefore, it is concluded that it is better to reduce the contribution of the genset when the power demand is low (DF and IDF strategies, Fig. 3), rather than mantaining a high efficiency operation and charging the LIB with the surplus power (GF and IGF strategies, Fig. 3).

Regarding the different terms of the LCC, the operation cost, and particularly the diesel consumption, are proven to be crucial. The general trend shows that the solutions that obtain lowest diesel consumption are the ones reducing more the LCC. The only exception is the SM strategy, which obtains a higher diesel consumption than DF and IDF, even if the LCC is reduced or equaled.

C. Analysis of LIB Technologies

The comparison of the results obtained by the different LIB chemistries concludes that LTO and NMC technologies achieve the best results. The difference between both technologies can be negligible, since LTO obtains better results in GF (-0.3%), IDF (-0.1%) and DP (-0.6%), but it can not improve NMC results in IGF (+0.5%), DF (+0.5%) and SM (+0.2%). The adquisition costs are higher in LTO due to the high price of the technology. However, compared to NMC, the final LCC is improved due to the lower operation costs, particularly, due to the lower required overhauls. LFP obtains the highest LCC in all the strategies, being always around 4-6% higher than the other technologies. As in LTO, the acquisition costs are high, but in this case the operation costs are not lowered. Consequently, the LCC is higher than in LTO and NMC.

VI. Conclusions

The current study has presented a LCC analysis for railway projects involving H-DEMUs, focused on the comparison of 3 LIB technologies and 6 EMSs. The obtained results have demonstrated the feasibility of the battery-based H-DEMU topology compared to the traditional DEMU. Related to the LIB technologies, LTO and NMC obtain the best results, showing always LCC values around 4-6% lower than LFP. From the proposed D-RB strategies, SM obtains the most promising results. When integrating LTO and NMC, SM improves the LCC of the DEMU between 13.2-13.4%, and it is just 2.0-2.8% ahead of the LCC obtained by the G-OP strategy (which is hardly applicable in real operation). Future developments may consider G-OP strategies that can be implemented on-line, or an extension of the LCC analysis in order to consider scenarios with different characteristics.

Acknowledgment

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