Hybrid Locomotive Applications for an Australian Heavy Haul
Train on A Typical Track Route

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Summary: A computer simulation technique – the longitudinal train simulation (CRE-LTS) software has been used to study and evaluate the potential of hybrid locomotive applications in the heavy haul operations on a typical track route in Australia. The study envisages a freight heavy haul operation on coastal undulating track rather than typical pit-to-port operations with large altitude change [1], [2]. Based on the simulation results, the train energy usage and the energy from dynamic braking are analysed. The simulation results showed that the locomotives operate at an average power of much less than 100% full power. An energy hybridisation potential factor is used to evaluate the hybridisation possibility, with its value of 54%. It means that there is high potential for hybrid heavy haul locomotive applications. Methods for practical hybrid applications are suggested and discussed.

1. INTRODUCTION

By improving the energy usage efficiency and using the regenerative electric energy that is currently wasted as heat in dynamic braking systems, rail heavy haul industry can reduce fossil fuel consumption and reduce carbon emissions. The energy generated by dynamic braking is about 10 – 30% of total locomotive energy usage based on [3]. It is necessary to consider new cost effective technologies to collect, store energy and reuse it. The options considered for a rail hybrid locomotive will depend on the track topography, locomotive tasks (i.e. shunting, passenger, heavy haul etc.) [4] and characteristics of available energy storage devices [5]. A diesel-electric based hybrid locomotive with energy storage devices (i.e. batteries, super-capacitors etc.) is a possible option to reduce fuel consumption and to provide a better overall fuel economy.

RailPower Technologies Corporation in Canada developed the first hybrid diesel-electric switcher locomotives (the Green Goat) in 2002 [6]. The Green Goat performed several tests at various locations. The test results confirmed quieter and easy operation with significant fuel saving. Depending on operating condition, the Green Goat can achieve fuel saving in the range of 50-80% and reduce harmful emissions by 80-90% as compared to traditional switcher locomotives. GE has considered employing similar technology to the Green Goat [7]. The combination of a smaller engine and an energy storage device with sodium nickel chloride batteries may provide a solution to environmental and economic challenges for railroad operators for the specific switcher locomotive application. ALSTOM [8] has renovated traditional diesel-hydraulic shunting locomotive into a hybrid shunting locomotive also using battery technology. The small diesel engine is used to recharge an energy storage device with 5800kg nickel cadmium (NiCd) batteries. They expected that this hybrid shunting locomotive will save average 40% fuel consumption, with a halving of particulate, NOx and CO₂ emissions. Noise might also be reduced by 15 dB.

HITACHI [9] – [10] has been working on the development of railway systems that utilize storage battery control technology to help the railway industry become more energy efficient and emit less CO₂ since 2001. The regenerative energy obtained from deceleration is returned to the power supply line so that it can be reused in any other trains on the line. They used the bank of 48 lithium-ion battery modules rated at 1 kWh each to store regenerative braking energy.

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It is expected that around 80% of regenerated energy will be recovered during braking and fuel consumption could be reduced by about 20%. The JR Freight in Japan launched a prototype diesel-battery hybrid shunting locomotive [11]. This hybrid shunting locomotive uses lithium ion batteries, which are recharged by the diesel engine. The batteries are also used to store regenerative braking energy. Comparing with diesel shunting locomotive, the hybrid shunting locomotive is expected to reduce noise by 10 dB and emissions by up to 40%.

Rail operations also have further potential options for energy savings by optimising the driving style to maximize the use of regenerated energy, and by careful management of the energy storage device [5].

An energy storage system was theoretically proposed [3] for the diesel-electric train in Spain to achieve a better efficiency without impairing the train’s dynamic characteristic (i.e. tractive effort etc). A software program using MATLAB was developed to evaluate the storage needs and the power and energy demand of the train in the specific track route with high gradient profile. The dynamic braking energy was collected and 10% fuel savings achieved by implementing the energy storage system. The train-energy simulator called TrEN was used to evaluate the potential of hybrid inter-city trains in UK routes [10]. The simulation of hybrid trains with range of lithium-ion battery capacities (up to 140kWh) on specific routes was conducted in order to find an optimum value of battery capacity. It was found that a battery capacity of 80-100kWh is sufficient for typical hybrid inter-city train in UK, which could reduce fuel consumption by 8-25%.

In this paper, the locomotive energy analysis through simulations on a typical track route in Australia is at first conducted using a Longitudinal Train Simulation (CRE-LTS) software package with further data processing using Matlab. An energy hybridisation potential factor is then defined to evaluate the potential for the hybrid heavy haul locomotive applications. It is found that there was high potential benefit in this application. Various approaches to hybridisation are then considered and discussed.

2. LONGITUDINAL TRAIN SIMULATIONS

Longitudinal Train Simulation (CRE-LTS) software was used to study the energy usage for the heavy haul operations on a typical track route in Australia and to evaluate the potential of hybrid heavy haul locomotive applications.

2.1 Train-Track Modelling

In the train modelling [11], each vehicle mass is modelled separately connected by the non-linear draft gear connection modelling and slack elements. The input parameters include the train configuration data, the locomotive and wagon data, the track data (tracle curvature, cant and grade) and the control data including fuzzy controller. The output parameters include the train operation speeds, the locomotive engine throttle notches, the coupler forces, the locomotive traction forces and the locomotive energy usage, etc.

A typical freight track line in Australia is selected for the simulations and its main data – track elevation and track curvature are shown in Fig. 1.

![Figure 1: Track Data](image-url)
In Fig. 1, the total track length is about 1600 km, with the maximum elevation being close to 100 m. The train is configured with 4 locomotives and 120 wagons and has a payload of 5453 tonnes. The maximum track speed is 80 km/h.

### 2.2 Power Usage Study

The train is required to operate in the following two cases:
- Only full dynamic braking (DB) is allowed;
- Full DB is priority, plus air braking.

Fig. 2 shows the locomotive energy usage and its average value for these two cases respectively.

From Fig. 2, the energy usage peaks supplied by the train’s diesel generators rise to 1.814 kWh per second for both cases while the average energy values are 0.8524 kWh per second and 0.8513 kWh per second respectively. Similar to the definition of the power hybridisation potential factor ($PHP = 1 - \frac{P_{\text{DB}}}{P_{\text{max}}}$) in [12], the energy hybridisation potential factor is defined as:

$$EHP = 1 - \frac{E_{\text{DB}}}{E_{\text{max}}} \quad (1)$$

Based on Eq. (1), the energy hybridisation potential factors are 54.1% and 54.2% respectively. There is high potential benefit for the hybrid locomotive applications. In addition, for about 40% of the trip, the diesel generator operates at lower loading (less 25%) and is only at its full power for one third of the trip, as shown in Fig. 3. It has been well known that the diesel engine energy efficiency and pollution are not optimal at lower loading, but are much better at higher loading. It is clear that this type of locomotive is not optimally used.
3. METHODS FOR LOCOMOTIVE HYBRIDISATION

For the diesel heavy haul hybrid locomotive applications, there could be three approaches (or modes):

1. Passive System (Regenerative Storage) (Mode #1) – the stored energy from regenerative energy from dynamic braking feeds the locomotive motors when the full power is required, so the locomotive generator can provide less full power in order to save fuel. There is potential for storage to be on-board or on a connected wagon (e.g. a ‘battery tender’).

2. Smaller Locomotive Design (Mode #2) – the big diesel generator (e.g., 3280 kW) is replaced with a smaller one capable of providing a maximum power and is coupled with an energy storage system (ESS) (typically batteries, flywheel and supercapacitors) in order to provide the fluctuating power (Again the storage is on-board or on a connected wagon). During the phases of lower demands (i.e. when the loading power is lower than the generator capacity), the ESS accumulates the energy from the generator and dynamic braking and restores it. When the power demands exceed the diesel generator capacity, the ESS releases the energy. Under these conditions, a smaller diesel generator will operate most of the time at its maximum power and will reduce diesel fuel consumption and pollution.

3. Pseudo Locomotive Design (Mode #3) – an energy storage system (ESS), motors and transmission system are designed (i.e. replacing the passive ‘battery wagon’ or ‘battery tender’ and taking advantage of the additional adhesion of the additional traction motors). This would look very much like a “Green Goat” locomotive, but configured as a slave unit. In this mode, one or more locomotives from the original locomotive fleet can be removed and replaced by the pseudo locomotive(s). The ESS on the pseudo locomotive(s) collects the energy from dynamic braking, and when the loading power is lower than a nominal power, it also accumulates the energy from the generators on the remaining locomotive(s). The remaining locomotive(s) operate(s) most of the time at full loads, which will also improve the diesel-electric generator energy efficiency and reduce the pollution.

4. CALCULATIONS FOR LOCOMOTIVE HYBRIDISATION

The locomotive hybridisation Modes #2 and #3 have been calculated and presented for the above two cases with the consideration of efficiencies. The efficiency is considered for the energy conversion during the trip. The following parameters are assumed:

- \( \eta_{d/e} \) – Efficiency of work done by the DB converting into the electrical energy (\( \eta_{d/e}=0.9 \)),
- \( \eta_{e_{ESS}} \) – Efficiency of recharging of the energy storage system (ESS) (\( \eta_{e_{ESS}}=0.9 \)),
- \( \eta_{c_{ESS}} \) – Efficiency of charging of the ESS (\( \eta_{c_{ESS}}=0.9 \)), and
- \( \eta_{m} \) – Efficiency of drive motor (\( \eta_{m}=0.8 \)).

The calculation results for Mode #2 are shown in following Fig. 4 for Case #1 and Case #2.

In Fig. 4 (a) and (b), the total maximum power values of 3318.6 kW and 3356.6 kW are selected for the smaller locomotives in these two cases. In this new configuration the four 1633kW locomotives would be replaced with four locomotives with the maximum power of 830kW (i.e., 3318.6/4 or 839kW (i.e., 3356.6/4) respectively for the two Cases. Hence, the smaller diesel generator will operate most of the time at its maximum power. When the loading power is lower than the generator capacity (the maximum power), the ESS accumulates the energy from the generator and dynamic braking and restores it. When the power demands exceed the diesel generator capacity, the ESS releases the energy (see the lower graphs). Fig. 4 (c) and (d) show the accumulative energy discharged from ESS and the accumulative energy recharged to ESS from the diesel generator and dynamic braking. The released energy from ESS is just equal to the recharged energy to ESS with considering efficiencies, which are shown in Fig. 4 (e) and (f). It can be seen that there is no significant difference between the Case #1 and the Case #2. The air braking, Case#2, does not alter the results much as most deceleration was still achieved using mainly dynamic brakes.

The calculation results for Mode #3 are shown in following Fig. 5.

In this Mode, one locomotive will be removed and replaced by a pseudo locomotive powered by an ESS, (“ESS locomotive”). In this configuration the locomotive group is made of three of the original 1633kW locomotives and an ESS locomotive (a vehicle made up of traction bogies, traction control and energy storage system). In Fig. 5 (a) and (b), the nominal power value was set at 694 kW or 705.5 kW for the remaining locomotive in these two cases respectively. That is an operating point. Therefore, the diesel generator in the three original locomotives will operate most of the time at the power larger than its nominal power, as shown in the upper graphs of 5 (a) and (b). In the lower left graphs of 5 (a) and (b), the traction power is just equal to the traction power of the originally replaced locomotive. When the loading power is lower than the nominal power, the ESS accumulates the energy from the generator and dynamic braking and restores it (see the lower right graphs). Fig. 5 (c) and (d) show the accumulative energy discharged from ESS and the accumulative energy recharged to ESS from the diesel generator and dynamic braking. The released energy from ESS is just equal to the recharged energy to ESS with considering efficiencies, which are shown in Fig. 5 (e) and (f).
Figure 4: Calculations for Mode #2
Figure 5: Calculations for Mode #3
5. CONCLUSIONS

A typical freight track route for the heavy haul operations in Australia have been selected to study the locomotive energy usages using the Longitudinal Train Simulation (CRE-LTS) software package. The simulations indicate that the diesel generators operate at the low loading (0 – 25%) for about 40% of the journey and less than 33% of the journey at full load (75 – 100%). An energy hybridisation potential factor is used to evaluate the hybridisation possibility, with its value found to be 54%. There is high potential for hybrid heavy haul locomotive applications. Three hybrid locomotive designs have been put forward. The analysis shows that the hybrid locomotive application Mode #2 – smaller locomotive design can be realised, e.g., four smaller locomotives with each having the maximum power value of 850 kW can be used to replace the existing four locomotives with each maximum power output of 1633 kW, which can save the fuel via the improved energy efficiency. The further analysis shows that the hybrid locomotive application Mode #3 – pseudo locomotive design can also be realised, providing savings but retaining three 'standard' locomotives.

Simulations have been done for the proposed designs for two cases of train operations. For each design has been performed the following cases: one is full dynamic braking (DB), and other is full DB plus air braking. As a result, it was confirmed that the options of rail hybrid heavy haul locomotive will not only depend on the track topography and train configuration (i.e., locomotive characteristics, locomotive and wagon numbers, etc.), but also the train operation (i.e., loading, DB, speed, etc.).

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REFERENCE


