Modeling and Control of Heavy Haul Trains

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Heavy haul trains up to several kilometers long, as illustrated in Fig. 1, are widely used to transport minerals in South Africa. The cost of train scheduling and human resources can be reduced when long and heavy haul trains are used instead of short trains. Energy consumption, running time, and in-train forces are the main concerns relating to the control of long heavy haul trains [1].

Braking control is a fundamental issue in heavy haul train operations when in-train forces and safe operation are considered. As an improvement of the older pneumatic braking systems, electrically controlled pneumatic braking systems developed in the 1990s provide various benefits, for instance, instantaneous response to the engineer's commands on all vehicles, graduated release of brakes, and continual replenishment of braking air reservoirs [2]. To improve the operational performance of heavy haul trains, energy-saving entails speed-switching or distance-switching algorithms, where the operation of a train consists of periods of powering, coasting, and stopping [3], [4]. The algorithms are based on a mass-point model, and the braking actions are assumed to be sparsely applied within the cruising period.

In [5], an LQR optimal algorithm is adopted to minimize the coupler forces and velocity deviations from their reference values. Due to the large number of variables and the corresponding constraints, the train model is simplified, and a linearized model is developed in [5] to calculate the control law. In [1], a heuristic optimal algorithm is applied to compute the equilibria of the system. The driving force is equally distributed to the locomotives, while the braking force of the wagons is either zero or evenly distributed to all wagons. This heuristic scheduling sometimes results in clashes between wagons, especially when one locomotive group is climbing uphill and the other is driving downhill. In [6], an open-loop scheduling algorithm is developed to optimize the equilibria of train operation. Three strategies, namely, 1-1 strategy, 2-1 strategy, and 2-2 strategy, are presented below for modeling operations of heavy haul trains. Based on this open-loop scheduling, an LQR control law is investigated in [7] with state feedback, and a speed regulator is also given in [8] with partial speed feedback. Partial speed feedback is used for fault-tolerant control in [9] to correct faults resulting from the braking system and sensors.

This article aims to provide an overview of the modeling and control of heavy haul trains from an energy-efficiency viewpoint. For this purpose, a unifying classification of energy efficiency in terms of performance, operation, equipment, and technology (POET) is presented and then applied to heavy haul train control problems. A heavy haul train is an energy system, and its cruise control can be viewed as an energy-efficiency control under this classification of energy-efficiency components. As shown in this article, heavy haul train control technologies can be included in POET-based energy-efficiency control for operational performance improvement of a heavy haul train.

According to the IEEE energy-management standard [10], the main components in energy management are meters and measurement, demand and energy limiters, highly efficient energy devices, energy-control systems, and load scheduling. Fig. 2 demonstrates a structured one-to-one correspondence between energy management and control systems [11]. Energy-efficiency components include management, operations, billing, maintenance, conversion, and fuel [12]-[14].

CONTROL OF HEAVY HAUL TRAINS

Traditional control of heavy haul trains with pneumatic control (PC) braking systems exhibits poor energy efficiency, slow running speed, possible derailment, and limited train length [6]. Independent distributed power (iDP) and electronically controlled pneumatic (ECP) braking systems are developed to overcome these difficulties [2]. iDP allows multiple locomotives to be distributed within the wagons and to be independently powered. Electric brake signals are received by all wagons simultaneously in ECP braking, and the braking effort can vary for different wagons. ECP braking, used on a large scale by the train operator Spoornet in South Africa on its COALink since 2002, shows improved safety and reliability. ECP braking has a 40-60% shorter stopping distance, 7-15% energy savings, 20-25% increased brake block and wheel life, and 20-25% decreased coupler and draft gear failures in practical applications [15]. Fig. 3 [11] from Spoornet shows the advantage of ECP versus classical PC. For a train with 150 cars, part (b) of Fig. 3 shows that ECP needs 10 s to increase the braking pressure from 0 PSI to 65 PSI, while part (a) of Fig. 3 shows that PC needs 175 s to increase to the same pressure. The ECP, together with the iDP, operator interface unit, train-line communication controller, train-line power controller, and car control device, constitute the EP-60 system, which implements train control instructions. Therefore, the efficiency of EP-60 at the equipment level is characterized by the requirement that specifications of the equipment must be strictly adhered to. Usually the equipment efficiency of EP-60 is monitored by the lower level controllers embedded in the control devices of the cars.

In evaluating equipment efficiency, EP-60 is usually regarded as being separated from the train system and having little interactive effect on other equipment. The equipment efficiency of EP-60 is evaluated by its capacity, specifications, constraints, standards, and maintenance. For instance, the braking capacity of EP-60 is much higher than that of the traditional PC; the American Railway Engineering and Maintenance-of-Way Association's standards specifying the features and requirements in pneumatic braking systems must be adhered to; and a well-organized maintenance program is needed to keep equipment efficiency at expected levels [16].

To analyze the in-train forces, we use the cascaded mass-point model [1]-[4], [5], [17]

$$m_s\dot{v}_s = u_s + f_{in_{s-1}} - f_{in_s} - f_{a_s}, s = 1, 2, \ldots, n, \tag{1}$$

$$\dot{x}_s = v_s - v_{s+1}, s = 1, 2, \ldots, n-1, \tag{2}$$

where m_s and v_s represent the mass and speed of the s-th car, respectively, x_s is the displacement of the s-th car, u_s is the drag or brake force, $f_{a_s} = f_{aero_s} + f_{p_s}$, $f_{aero_s} = m_s(c_{0_s} + c_{1_s}v_s + c_{2_s}v_s^2)$ is the aerodynamic force, and $f_{p_s} = f_{g_s} + f_{c_s}$ is the force due to track slope and curvature.

Due to the equipment limitations, the parameters and variables in equations (1) and (2) satisfy the boundary constraints

$$\underline{U}_i \leq u_i \leq \overline{U}_i, i = 1, 2, \ldots, n, \tag{3}$$

$$\underline{F}_{in_j} \leq f_{in_j} \leq \overline{F}_{in_j}, j = 1, 2, \ldots, n-1, \tag{4}$$

where $\underline{U}_i, \overline{U}_i, \underline{F}_{in_j}, \overline{F}_{in_j}$ are constants [6]. In practice, the control input u_i corresponds to the traction force and braking force, which are limited by the capacities of the locomotives and the braking system. Furthermore, the in-train force f_{in_j} is related to the safe running of the train, for instance, the safety range of the in-train force for COALink trains is from -2,000 kN to 2,000 kN [15]. We assume throughout the article that the train with n cars in (1) and (2) has k locomotives, which are the l_1-th car, l_2-th car, $\ldots$, l_k-th car with $1 \leq l_1 < l_2 < \ldots < l_k \leq n$, $k \geq 1$. More involved models that include ride comfort are considered in [18], [19].

Control strategies

The control strategies labeled 1-1, 2-1, and 2-2 represent different ways of driving the locomotives and braking the wagons. In the 1-1 strategy, the control system has one control signal for all the locomotives and one braking signal for all wagons, for example, the following locomotive can be driven in tandem with the leading one. In the 2-1 strategy, locomotives are powered and controlled independently, while braking force is applied uniformly for all wagons. In the 2-2 strategy, the locomotives and wagons can be controlled independently.

For control system analysis, linearization of (1) and (2) at an operating point is needed. Let $f^0_{in_j}(x^0_j)$, $v^0_i(v_r)$, and u^0_i be, respectively, the in-train forces, velocities, and the control input of tracking or braking forces in steady state, which is chosen as the operating point of linearization, where $j = 1, \ldots, n-1$, $i = 1, \ldots, n$. Then the train model is rewritten as [7]

$$\delta \dot{v}_s = (\delta u_s + \delta f_{in_{s-1}} - \delta f_{in_s} - \delta f a_s)/m_s, s = 1, \ldots, n, \quad (5)$$

$$\delta \dot{x}_j = \delta v_j - \delta v_{j+1}, j = 1, \ldots, n-1, \quad (6)$$

where $\delta v_s = v_s - v_s^0 = v_s - v_r$, $\delta u_s = u_s - u_s^0$, $\delta f_{in_s} = f_{in_s} - f_{in_s}^0$, $\delta x_j = x_j - x_j^0$, and v_r is the reference speed. When the damping of the coupler is ignored, equations (5) and (6) are linearized as [15]

$$\begin{aligned}\delta \dot{v}_s &= (\delta u_s + k_{s-1}\delta x_{s-1} - k_s \delta x_s)/m_s - (c_{1_s} + 2c_{2_s} v_r)\delta v_s, s = 1, 2, \ldots, n,\\ \delta \dot{x}_j &= \delta v_j - \delta v_{j+1}, j = 1, \ldots, n-1,\end{aligned}$$

where k_s is the linearized coefficient of the coupler with the assumption $k_0 = k_n = 0$. This model can be rewritten as

$$\dot{X} = AX + BU, \tag{7}$$

where

$$\begin{aligned}
X &= \text{col}(\delta v_1, \ldots, \delta v_n, \delta x_1, \ldots, \delta x_{n-1}),\\
U &= \text{col}(\delta u_1, \ldots, \delta u_n),\\
A &= \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix},\\
A_{11} &= -\text{diag}(c_{1_1} + 2c_{2_1} v_r, \ldots, c_{1_n} + 2c_{2_n} v_r),\\
A_{22} &= 0_{(n-1)\times(n-1)},\\
B &= \begin{bmatrix} B_1 \\ 0_{(n-1)\times n} \end{bmatrix},\\
B_1 &= \text{diag}(\tfrac{1}{m_1}, \ldots, \tfrac{1}{m_n}),\\
A_{12} &= \begin{bmatrix} -\frac{k_1}{m_1} & 0 & \ldots & 0 & 0 \\ \frac{k_1}{m_2} & -\frac{k_2}{m_2} & \ldots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \ldots & \frac{k_{n-2}}{m_{n-1}} & -\frac{k_{n-1}}{m_{n-1}} \\ 0 & 0 & \ldots & 0 & \frac{k_{n-1}}{m_n} \end{bmatrix},
\end{aligned}$$

$$A_{21} = \begin{bmatrix} 1 & -1 & 0 & \dots & 0 & 0 \\ 0 & 1 & -1 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 1 & -1 \end{bmatrix},$$

and the parameters $k_i, i = 1, \dots, n-1$, are chosen to be constant.

The linearized model (7) has an n-dimensional input U, which implies that there are n independent drag and brake forces. Therefore, the physical model (7) corresponds to the 2-2 strategy.

If the controls u_1, …, u_n are independent, then the 2-2 strategy needs an independent control signal for each car, which is not practically possible because of the limited bandwidth for control signals in the communication system. Therefore, adjacent wagons that have the same mass and experience similar track conditions are controlled as one group, and thus fewer control signals are needed [20]. With this idea in mind, one control signal for different cars within the same group is applied. Assume that the n cars are divided into κ groups, and the control inputs for the κ groups are $U_1, \dots, U_\kappa$. This kind of grouping of cars, which is called fencing [20], assumes that a fence exists between two adjacent groups. The notation $F = [f_1, \dots, f_{\kappa-1}]$ represents the fencing, where f_j is the first car after the j-th fence [20]. For instance, $F = [2, 4, 7]$ for a train with ten cars means that there are three fences and thus four groups in the train; the first group is the first car; the second group consists of the second and third cars; the third group consists of the fourth, fifth, and the sixth cars; while the rest of the cars belong to the fourth group. Letting $\overline{U} = (U_1, \dots, U_\kappa)^T$, the linearized model (7) can be rewritten as

$$\dot{X} = AX + \overline{B}\,\overline{U}, \tag{8}$$

where X and A are given in (7),

$$\overline{B} = \begin{bmatrix} B_2 \\ 0_{(n-1)\times\kappa} \end{bmatrix},$$

and B_2 is an $n \times \kappa$ matrix. Note that when κ equals n, the model (8) includes (7) as a special case. The rows of the matrix B_2 can also be grouped according to the grouping criteria.

A group is a set of row vectors from B_2 such that each row of B_2 belongs to a group. Each group has rank one as a set of row vectors, and each pair of vectors from different groups must be independent.

An example for the 1-1 control strategy is a train with five cars. For a fencing $F = [2]$, we have

$$B_2 = \begin{pmatrix} \frac{1}{m_1} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{m_2} & \frac{1}{m_3} & \frac{1}{m_4} & \frac{1}{m_5} \end{pmatrix}^T. \tag{9}$$

The fencing $F = [2]$ can be recovered by grouping the rows of B_2 so that the first row and the remaining four rows form the two groups, respectively. By using the grouping criteria, this example can be generalized to the proposition below.

Proposition. Assume that a train has $n > 3$ cars, where k of them are locomotives, the remaining $n - k$ cars are wagons, and the k locomotives include the l_1-th, l_2-th, $\ldots$, and l_k-th cars. Let B_2^1 denote the submatrix of B_2 formed by the l_1-th, l_2-th, $\ldots$, and l_k-th columns, and let B_2^2 denote the submatrix formed by the remaining columns of B_2 . Then the control strategy for the train system modeled by (8) is as follows:

(i) 1-1 strategy if and only if rank $B_2 = 2$;

(ii) 2-1 strategy if and only if rank $B_2^1 > 1$ and rank $B_2^2 = 1$; and

(iii) 2-2 strategy if and only if rank $B_2^1 > 1$ and rank $B_2^2 > 1$.

Furthermore, the structure of the matrix B_2 determines the fencing F for the train model, and vice versa.

The 1-1, 2-1, and 2-2 control strategies are evaluated and tested for their feasibility both technically [1], [20] and financially [2]. These evaluations are used to assess technology efficiency for its feasibility, life-cycle cost [21], return on investment [22], and capability of energy converting, processing, or transmitting [23].

Control objectives and optimal controllers

Control objectives of the train model can be formulated by considering indicators of performance efficiency, which are determined by external but deterministic system indicators, such as running time, fuel cost, energy sources, technical indicators, socio-economic indicators, and environmental impact. For instance, minimizing the objective function

$$J_1 = \sum_{i=1}^{n-1} f_{in_i}^2, \tag{10}$$

can be used to optimize in-train forces, which provides a technical indicator for safety [6]; minimal fuel cost is achieved by optimizing [7]

$$J_2 = \sum_{i=1}^{n} u_i^2;$$

and the desired velocity $w_i(t)$ of the i-th car can be tracked over a fixed time period $[0, T]$ by minimizing

$$J_3 = \int_0^T \sum_{i=1}^{n} (v_i(t) - w_i(t))^2 \mathrm{d}t.$$

Note that velocity tracking is both a technical and a socio-economic indicator.

A multi-objective optimal control problem needs to be solved if the goal is to minimize more than one of the objectives J_1, J_2, J_3. A typical approach to solving the multi-objective problem is to transform the problem into a single objective optimal control problem. For example, [7] minimizes both the in-train forces and the energy usage by minimizing

$$J = K_f \sum_{i=1}^{n-1} f_{in_i}^2 + K_e \sum_{i=1}^{n} u_i^2, \tag{11}$$

where the weights of the in-train force and energy consumption are K_f and K_e, respectively. The weighting factors K_f and K_e indicate a balance between the safety and energy costs. The objective function

$$J = K_f \sum_{i=1}^{n-1} f_{in_i}^2 + K_e \sum_{i=1}^{n} u_i^2 + K_v \int_0^T \sum_{i=1}^{n} (v_i(t) - w_i(t))^2 \mathrm{d}t, \tag{12}$$

indicates a balance among in-train force, energy consumption, and velocity tracking, where K_v is a weighting factor for the velocity tracking part. This objective function is similar to those used in [7], [8].

Open-loop control

For open-loop control, the train is assumed to be in a steady state mode that satisfies [6]

$$\begin{aligned} \frac{\mathrm{d}v_i}{\mathrm{d}t} &= a, i = 1, 2, \ldots, n, \\ \frac{\mathrm{d}x_j}{\mathrm{d}t} &= 0, j = 1, 2, \ldots, n-1, \end{aligned}$$

where a is the acceleration, which is zero when the train is cruising and a_r $(-a_r)$ when the train is running within a scheduled acceleration (deceleration) period. These steady state constraints lead to the constraint [6]

$$\sum_{i=1}^{n} u_i - \sum_{i=1}^{n}(f_{a_i} + m_i a) \;\; = \;\; 0. \tag{13}$$

If the 1-1 strategy is employed, all of the locomotives equally share the drag forces, and the brake forces for all wagons are equal. Therefore,

$$u_{l_1} = u_{l_2} = \cdots = u_{l_k} \triangleq u_t,$$
$$u_i \triangleq u_b, i \in \{1, 2, \ldots, n\} \backslash \{l_1, l_2, \ldots, l_k\}.$$

To optimize the open-loop controller, let u_t be the locomotive drag force, u_b the wagon brake force, and J the objective function to be minimized, then the controller is given by [6]

$$\frac{\partial \bar{J}}{\partial u_t} = 0, \qquad \frac{\partial \bar{J}}{\partial u_b} = 0,$$

where

$$\bar{J} = J + 2\lambda(ku_t + (n-k)u_b - \sum_{j=1}^{n}(f_{a_j} + m_j a)),$$

and λ is the Lagrange multiplier. For instance, for a train with 52 cars in which the first car and the last car are locomotives while all the other cars are wagons, then the optimal controller for the objective function (10) is [6]

$$u_t(t) \;\; = \tfrac{1}{2262} \sum_{i=1}^{52} \tfrac{-3888 - 25i + 5i^2}{2} (f_{a_i} + m_i a), \tag{14}$$

$$u_b(t) \;\; = \tfrac{1}{2262} \sum_{i=1}^{52} \tfrac{1230 + 5i - i^2}{10} (f_{a_i} + m_i a). \tag{15}$$

The open-loop controller in (14), (15) shows that the operation efficiency of the train is optimized by coordinating various system components, which include equipment and time. For example, the drag and brake forces must match well with the in-train forces, accelerations, and decelerations at each time to reach the optimal objective.

The open-loop controllers for 2-1 and 2-2 control strategies can be solved in a similar manner. The 1-1, 2-1, and 2-2 control strategies are compared to classical heuristic scheduling in Table 1 [15] for the objective function (11) with weighting factors $K_f = K_e = 1$. Table 1 shows that the effect of heuristic scheduling and 1-1 control on velocity tracking and in-train force are similar, however, 1-1 control consumes more energy than heuristic scheduling. The 2-1 strategy has the worst performance on energy consumption but the best in-train force performance, while the 2-2 strategy has the worst in-train force performance in terms of oscillation, the smallest speed-tracking error, and the overall best steady-state performance with respect to both in-train force and velocity tracking. Studies in [15] show that heuristic scheduling usually has the best energy performance, but its velocity tracking error and in-train force are greater than those obtained by the 2-1 and 2-2 control strategies. The velocity tracking error and possible oscillations remain the major drawbacks of open-loop controllers.

Closed-loop control

A closed-loop controller can be designed based on the linearized system of equations (7). When an LQR controller is designed, an objective function similar to (12) is chosen as [7], [20]

$$\delta J = \int_0^\infty \left(K_f \sum_{i=1}^{n-1} \delta x_i^2 + K_e \delta u_i^2 + K_v \sum_{i=0}^{n} \delta v_i^2 \right) \mathrm{d}t, \tag{16}$$

which can be written as

$$\delta J = \int_0^\infty (X^T Q X + U^T R U)\mathrm{d}t$$

for suitable matrices Q and R. The weights K_f, K_e, and K_v are used to obtain trade-offs among in-train forces, energy consumption, and velocity tracking. Similar to the open-loop control case, the LQR feedback controller $U = -KX$ requires that different system components act in a coordinative manner at all times.

Table 2 from [7] provides a simulation-based comparison for heuristic scheduling and optimal control under the 1-1, 2-1, and 2-2 strategies for the objective function (16), where the weights are chosen to be (K_f, K_e, K_v)=$(1, 1, 1)$ or $(1, 1, 10)$. Table 2 shows that the strategies 1-1, 2-1, and 2-2 under closed-loop heuristic scheduling have similar performance, whereas the 2-2 strategy under closed-loop optimal scheduling has better performance than the remaining strategies in terms of velocity tracking and in-train force. This closed-loop 2-2 optimal control scheduling also has better energy performance than the corresponding closed-loop 2-1 optimal control scheduling.

CONCLUSIONS

Modeling and control of heavy haul trains are discussed in this article from the perspective of the performance, operation, equipment, and technology (POET) energy-efficiency classification. The POET classification can also be applied in the study of other energy-management systems. For example, [24] studies the relationships among the POET components for energy-management systems with application to buildings and conveyor belts.

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(a)

(b)

Figure 1. Heavy haul trains of Spoornet, South Africa. (a) is a heavy haul train transporting iron ore, and (b) is a heavy haul train transporting coal in the COALink line of Spoornet. Such a heavy haul train usually has about 200 wagons that stretch 2.5 kilometers. Extremely long trains up to 10 kilometers in length are considered in the business plan of Spoornet.

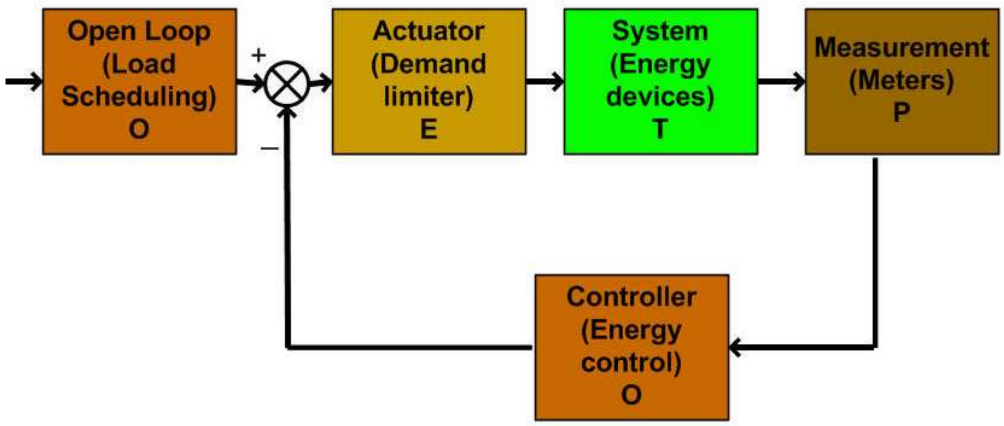
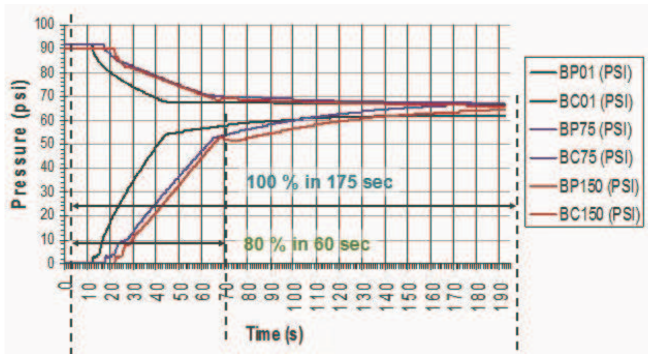
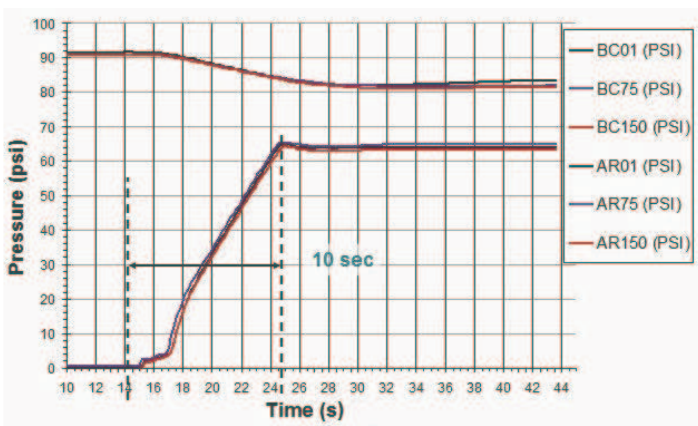


Figure 2. POET classification. Measurement in a control system or an energy system provides metered data to evaluate the external performance of the whole system, therefore, measurement and meters are classified as performance efficiency. Load scheduling or energy control improves energy efficiency through the control of internal system components, thus the open-loop solution, controller, load scheduling, and energy control are categorized into operation efficiency. A demand limiter performs as an actuator to implement the load scheduling plan, hence the demand limiter and actuator correspond to equipment efficiency. The design of energy devices and the control system needs advanced technology, and it lies in the content of technology efficiency.



(a)



(b)

Figure 3. Comparison of PC and ECP. (a) and (b) show the performance of PC and ECP braking systems, respectively. (a) and (b) also show the times needed to increase or decrease the pressure to given values for different control systems. This figure shows that ECP can increase the pressure from 0 PSI to 65 PSI about 16.5 times faster than PC.

Strategy	$\lvert\delta\bar{v}\rvert$(m/s)			$\overline{\lvert f_{in}\rvert}$(kN)			E
	max	mean	std	max	mean	std	(MJ)
Heuristic	3.9179	0.8225	0.53	390.23	143.85	98.86	8,520
1-1	3.7187	0.9410	0.54	392.13	144.81	101.83	11,400
2-1	3.5277	0.7460	0.54	420.31	118.51	70.42	23,300
2-2	3.0195	0.4152	0.46	498.59	141.43	103.73	16,400

Table 1. Comparison of open-loop heuristic scheduling and optimal control scheduling [15]. The first column corresponds to heuristic scheduling and the three 1-1, 2-1, and 2-2 optimal control scheduling strategies. The notation $\lvert\delta\bar{v}\rvert$ is the absolute value of the difference between the reference velocity and the mean value of all the cars' velocities, $\overline{\lvert f_{in}\rvert}$ is the mean value of the absolute values of all the couplers' in-train forces, and E is the energy consumption. The labels max, mean, and std denote maximum value, mean value, and standard deviations, respectively. In terms of the performance on velocity tracking and in-train force, the 1-1 strategy optimal scheduling is similar to the heuristic scheduling, while the 2-2 strategy has the best steady-state performance.

	Strategy	$\lvert\delta\bar{v}\rvert$(m/s)			$\overline{\lvert f_{in}\rvert}$(kN)			E
		max	mean	std	max	mean	std	(MJ)
$K_e = 1$	C01	3.3241	0.4573	0.58	386.94	145.82	100.27	8,700
	C02	3.3244	0.4539	0.57	376.78	145.30	99.32	8,610
$K_f = 1$	C03	3.3241	0.4613	0.58	373.60	144.45	97.50	8,470
	C1	3.2274	0.4992	0.56	387.04	147.52	102.65	11,760
$K_v = 1$	C2	3.1405	0.4585	0.53	318.97	106.16	59.35	22,100
	C3	3.0182	0.3166	0.48	454.50	97.40	86.44	16,500
$K_e = 1$	C01	3.0412	0.3062	0.55	394.39	145.72	99.57	8,620
	C02	3.0413	0.3080	0.55	394.50	144.54	100.07	8,550
$K_f = 1$	C03	3.0412	0.3085	0.55	369.24	144.61	96.63	8,586
	C1	3.0070	0.3372	0.57	382.57	147.38	102.40	11,100
$K_v = 10$	C2	2.9891	0.3629	0.53	344.95	103.57	67.20	21,800
	C3	3.0225	0.2443	0.50	408.70	74.07	76.34	16,500

Table 2. Comparison of various closed-loop train control strategies [7]. The notations $\lvert\delta\bar{v}\rvert$, $\overline{\lvert f_{in}\rvert}$, E, max, mean, and std are defined in Table 1. Control strategies C01, C02, and C03 are, respectively, the closed-loop 1-1 strategy, 2-1 strategy, and 2-2 strategy based on heuristic scheduling; while C1, C2, and C3 are, respectively, the closed-loop 1-1 strategy, 2-1 strategy, and 2-2 strategy based on optimal control. The top part of the table compares these control strategies for the weighting factors $K_e = K_f = K_v = 1$, while the lower part shows the comparison for the weighting factors $K_e = K_f = 1, K_v = 10$. This table shows that the closed-loop 2-2 strategy provides better performance than others in terms of velocity tracking and in-train force.

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