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Speed profile planning for train stopping motion in the shortest time considering ride comfort and braking performance under position-depending speed limits

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Abstract

Automatic train operation can realize the implementation of operation patterns that are difficult to achieve with human response characteristics, and can add value to train operation beyond labour savings, such as the implementation of energy-saving operation methods on actual trains. Feedforward control is important in automatic operation and is formulated as a speed profile generation problem. When the constraint conditions vary depending on the vehicle and track conditions. Guaranteeing ride comfort and low computational cost as well as energy saving are required for designing automatic operation. This study proposes a feedforward control design method for driving rail vehicles that gives a deceleration trajectory with minimum running time while satisfying position-dependent speed and acceleration constraints and acceleration and jerk limits imposed by ride comfort. The proposed method optimizes the stopping trajectory, which is a part of the vehicle's travel trajectory from start to stop. The proposed method is practical in two respects: the computational load is light, and the obtained trajectory is optimal in terms of travel time, ride comfort, and energy. Numerical simulations demonstrate the validity of the proposed method. The proposed method can be applied to quickly calculate the shortest-time running trajectory from the brake starting position and speed, which varies from run to run, to the stopping position.

Keywords: speed profile optimization, train stopping control, ride comfort, position-depending constraints

1 Introduction

Automatic train operation has been attracting attention in recent years to save labour and improve the quality of train operation, such as implementing energy-saving operation methods on actual trains. It can implement operations that are difficult to achieve with human response performance. Motion control in automatic train operation is to follow to the running trajectory. It is achieved by feedforward and feedback control[1]. The accuracy of position and speed detections in railway vehicles are poor[2], and the actuators such as motors and brake systems that drive the vehicle have a severe limit of output range relative to regular use and considerable time delay[3]. Therefore, it is crucial to design a smart feedforward control system that relies on feedback control as little as possible for the automatic operation of rail vehicles.

The feedforward control design in automatic operation is evaluated by running time, energy consumption, and ride comfort, often evaluated by the maximum value of acceleration and jerk[4].

The optimization of running trajectory to obtain the feedforward control trajectory is performed by various methods in many literatures. Methods based on dynamic programming[5] and other mathematical optimizations[6,7] aim energy-saving running trajectory. These methods can obtain optimal speed trajectories for complex constraints such as position-dependent speed limits, acceleration conditions, and running resistance. However, they have high computational cost. These previous studies show that for monotonically increasing or decreasing speed, it is most energy-efficient to use the maximum value of given speed, acceleration, and jerk limits[4]. By this principle, optimal trajectory can be calculated without complex optimization calculation.

This study proposes running trajectory generating method from the braking starting point to the stopping point using this fact. The proposed method is useful for optimizing the crucial part of running trajectory and can be used in combination with optimizing overall running trajectory. The proposed method has following advantages.

(i) can be used for advanced systems giving a continuous position and speed information and for conventional systems giving only discrete position and speed.

(ii) can relax brake force right before stopping by explicitly treating the jerk limit

(iii) can treat the effects of adhesion

(iv) feasible and precise calculation of the stopping trajectory, which is compatible with platform doors

This study can provide all automatic stopping operations needed under normal conditions, except for human disturbance to the track, which can only be handled by a feedback-based method.

2 Methods

This study proposes a method to calculate the shortest-time trajectory in a straightforward manner with low computational load. In reference [8], a method to obtain the shortest time trajectory without mathematical optimization is proposed for the case where the constraints of speed and acceleration is constant. the shortest time trajectory is calculated when there are position-dependent constraints based on the method in [8]. Riding comfort is guaranteed by keeping the maximum values of acceleration and jerk below the arbitrary given limits.

The following is the design method for the shortest-time speed trajectory. The shortest-time nature is guaranteed by the greedy method, which selects the running method to maximum speed, acceleration, and jerk at each time. We define the point at which the velocity or acceleration constraint changes as “event point”.

The shortest-time trajectory is obtained by repeating the selection of the four movements (a), …, (d) backward from the stopping point until the position of current point reaches to the initial braking position.

(a) If both speed and acceleration are less than the limit at the current point, apply positive jerk until the acceleration reaches the current limit.

(b) If acceleration is equal to the limit at the current point, apply constant acceleration to the next event point

(c) If speed is equal to the limit at the current point, apply constant speed to the next event point.

(d) If acceleration or speed exceeds the limit at the current point, return to the previous calculation point, and proceed using the driving method selected at that point to the intermediate point, add a negative maximum jerk driving from the intermediate point to the next event point. If the speed limit exceeds, the speed at the next event point has to be the limit and the acceleration has to be 0. If the acceleration limit exceeds, the acceleration at the next event point has to be the limit.

If the velocity at the initial braking position does not reach the final velocity, there is no feasible trajectory under the acceleration and jerk limits at that time. Relax the acceleration and jerk limits and solve again.

3 Results

We conducted numerical simulations in order to validate the proposed method. First, we describe the track and vehicle conditions used in the simulation. Parameters are shown in Table 1.

Next, we explain the trajectory generating results. We conducted numerical simulations on 2 cases of constraints, constant speed, acceleration limits, and position-dependent speed and acceleration limits.

First, Figure 1 and 2 shows the results of trajectory generation at constant speed and acceleration limit. An energy-efficient running trajectory was obtained at the maximum speed and applying one brake at the maximum deceleration to reach a stopping point. The acceleration was relaxed to meet the jerk limit before stopping, and the running trajectory satisfied riding comfort.

Next, Figure 3 and 4 shows the trajectory generation at position-dependent velocity and acceleration limits. The gradient resistance is $g \times 9.8/1000\ \mathrm{m/s^2}$ for a gradient g ‰, and the gradient resistance is added to the maximum deceleration limit to represent the maximum achievable deceleration effort on the gradient. An energy-efficient track running at as high as possible is obtained by braking at the maximum deceleration just before the speed limit and just before stopping. The acceleration was relaxed to meet the jerk limit and at the start and end of deceleration, and the running trajectory satisfied riding comfort. Before stopping and at the start and end of deceleration, acceleration was relaxed to meet the jerk limit. Optimal trajectory generation was achieved successfully in both two simple and complicated cases.

Parameter	Value
Distance	350 m
Initial speed	20 m/s
Maximum deceleration allowed for comfort	0.9 m/s^2
Maximum jerk allowed by the ride	0.6 km/h/s^3
Maximum deceleration allowed by adhesion	1.0 m/s^2
Gradient	0 m to 150 m: -20 ‰
	After 150 m: 0 ‰
Speed limit	0 m to 250 m: 20 m/s
	After 250 m: 10 m/s

Table 1: Parameters for the track and vehicle conditions for the numerical validation.

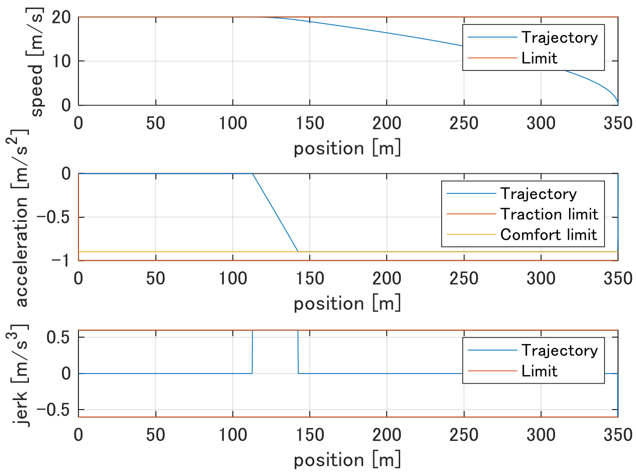

Figure 1: Position trajectory of position, speed, acceleration, and jerk with constant speed and time limits.

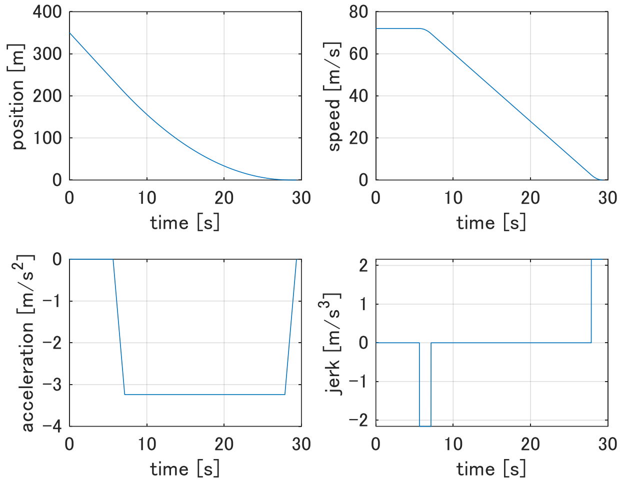

Figure 2: Time trajectory of position, speed, acceleration, and jerk with constant speed and time limits.

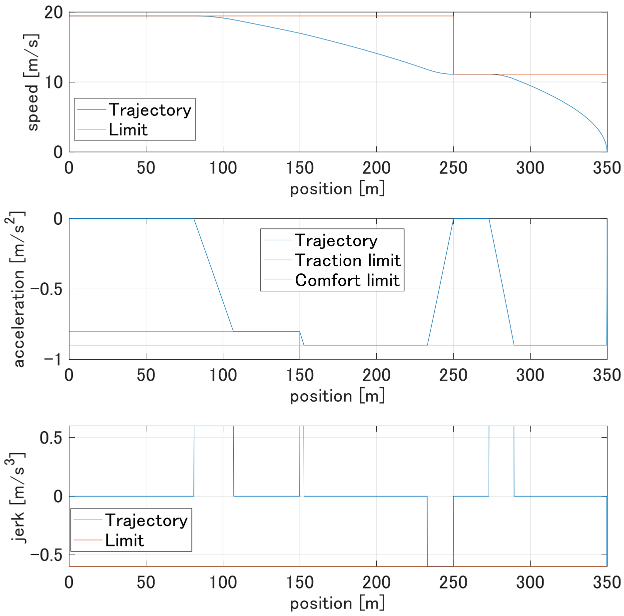

Figure 3: Position trajectory of position, speed, acceleration, and jerk with position-dependent speed and time limits.

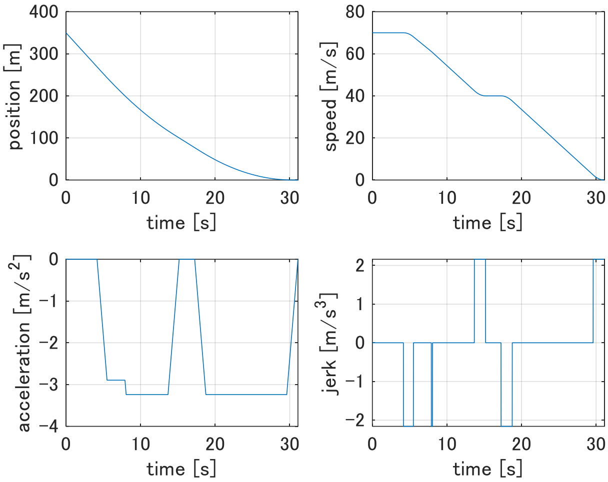

Figure 4: Time trajectory of position, speed, acceleration, and jerk with position-dependent speed and time limits.

4 Conclusions and Contributions

This study proposes a feedforward control design method for driving railway vehicle at given acceleration and jerk limits, and gives a deceleration trajectory that satisfies position-dependent speed and acceleration limits while moving in minimum time. The proposed method is practically useful in two respects: (1) the computational load is light because it only solves algebraic equations of third order or lower iteratively over points with varying speed and acceleration limits; (2) the resulting trajectory is optimal in terms of travel time, ride quality, and energy.

The proposed method optimizes the stopping trajectory, which is a part of the vehicle's running trajectory from start to stop. As an example of applications, it is possible to optimize a stopping control trajectory by considering ride comfort with the proposed method after the entire running trajectory is obtained by other mathematical optimization methods. Also it is possible to quickly calculate the minimum time trajectory from the brake starting position and speed, which vary in each run, to the stopping point on the running train.

As future work, we are considering generating a running trajectory that compensates for changes in road surface conditions by modeling changes in track adhesion conditions due to weather conditions as changes in the maximum deceleration for each run. Calculating the optimal trajectory by the varying maximum deceleration obtained by adhesion changes using the proposed method can achieve the aim.

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