Optimal Driving Aid for Speed Control of High-Speed Trains

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Recent development in computer technology and in cab signal systems has made automatic train speed control technically feasible. However, completely automatic control on high-speed passenger trains may not be easily accepted for various political, safety, or economical reasons. Therefore, humans remain in the cabs of high-speed trains. The question is, then, which tasks in train operations should be entrusted to the human and which to the computer? In view of the weakness and strength of humans and computers, we seek some kind of human-machine cooperation that combines the strength of the two agents in the cab and overcomes their weaknesses. An optimal solution of speed and thrust-braking profiles can be developed under the assumption that the speed limits across the trip from one point (which could be a station or any known point) to the next are known a priori and that the track and the train characteristics are known. An integrated speed control display based on this optimal solution presents the human driver with the optimal speed and thrust-braking profiles and other information relevant to speed control. Four different options of train speed control based on the proposed display are: (*a*) simple manual control, (*b*) manual control with the display as an aid, (*c*) manual control with the display as an aid plus the automatic control option, and (*d*) fully automatic control with emergency-override options. Considerations that bear upon the choice among the alternatives include basic system features, experimental results, view of human role in automation, introduction of new tasks for the human driver accompanying the automation, public anxiety, and liability in case of an accident.

The primary task in train driving is speed control. To perform this task well, the driver, whether human or machine, must know the track properties (grades, curvatures, etc.), the train properties (length, weight, propulsive power, characteristics of resistance and tractive forces, etc.), and the operating rules (speed limits, emergency handling procedures, etc.). As measurement technology develops and computer capability improves, fully automatic speed control becomes technically possible.

The question is, then, how should the available information and control capability be used? At one end of the utilization spectrum is manual control, which currently dominates most locomotive operations. At the other is completely automatic control. The former is demanding on the driver and is likely to result in less-than-ideal performance. The latter may not be easily accepted by the public for various reasons even if technology permits and will surely fail when the input information is incorrect.

Assuming full automation, keeping the human operator in the cab without an opportunity to participate in the control during normal operations has its problems. On the one hand, the human operator may develop complacency, low job satisfaction and other human factors problems, and may not be able to cope with emergencies in the way in which he or she is expected. On the other hand, machines lack the flexibility that humans have in handling abnormal or emergency situations. Some kind of human-machine cooperation that combines the strength of the two agents in the cab and overcomes their weaknesses is sought.

Automatic speed control in high-speed trains (more than 200 km/hr or 125 mph) has been used at different levels in different countries, depending on the types of braking facilities used. In Germany, speed control frequently takes the form of cruise control with the cruising speeds indicated by a display. This form of speed control, which can be inefficient in terms of energy consumption, is affordable because of the regenerative braking capability of trains. In France, by contrast, trains are controlled manually by using a written specification on the most efficient coasting strategy. Cruise control is rarely used because of the energy loss resulting from rheostatic braking.

Studies have been made on automatic dispatching that involves pacing trains over a territory by a train dispatcher to ensure travel according to an optimal velocity profile to save fuel (*1,2*). However, the issues of how the driver uses the velocity profile (a combination of throttle and brake settings) in cab and how it might be used for fully automated speed control have not been addressed.

This paper addresses the issue of human-machine allocation of train control tasks by proposing a scheme of train speed control. First, an optimal solution of speed and thrust-braking profiles for a high-speed train is described. Second, an integrated speed control display based on the optimal solution of speed and control profiles is proposed. Third, various possibilities of using the display as a speed-control decision aid for the human driver are discussed. The paper concludes with a brief summary and the authors' outlook on future works.

OPTIMAL HIGH-SPEED TRAIN CONTROL SOLUTION

Technically, it is now quite feasible to automate train speed control to keep the train within speed limits, adhere to the schedule, and, under these constraints, minimize energy consumption. Automatic measurement of train position, velocity, thrust, braking, and other variables has steadily improved and advanced cab signal systems are becoming available. Modeling of train dynamic characteristics is more precise with the advent of new technologies. Computers are becoming faster, cheaper, and more reliable, which allows implementation of some computationally demanding algorithms that were not possible earlier. Therefore, once the current location, time, and the scheduled next stop location of a train is known, it is possible to obtain an optimal solution of the speed control for its whole trip—optimal in terms of energy consumption.

The problem of an optimal solution to train speed control can be stated as follows: a train is known to traverse the section of track

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from point A to point B in T hours. Terminal speeds at the two points are known. (Note that points A and B could be the two stations of a trip or any other known points along the trip, as long as the train speeds at the two points and the time to traverse the section between them are known). The speed limits, track grades, and curvatures of the track blocks are known a priori. Related train dynamic characteristics, such as mass, tractive effort, and resistance force on a flat track (i.e., resistance induced by aerodynamics and factors not related to curvatures and grades), as functions of speed are also assumed to be known a priori. This implies that the total resistance force experienced by a train at any moment is the sum of those induced by track grades and curvatures and that on a flat track. The question is to find the speed profile that minimizes the energy consumption of the trip from A to B in T hours. This is a constrained optimization problem that can be solved with dynamic programming techniques. Figure 1 depicts the function of a dynamic programming algorithm. (Detailed mathematical derivation can be obtained from the authors.)

In applying the above optimal solution of train speed control, some practical considerations deserve special attention. Ideally, if the track geometry were known perfectly and the train model were perfect, the optimal speed and thrust-braking profiles could be calculated. This implies that these profiles can be simply followed, and train positions and velocities would never have to be measured. Since this ideal situation is not true, the only reasonable approach is to update the optimization repeatedly during the transit from point A to point B.

The updating should take the current actual (measured) train position, velocity, and time as the initial condition and current speed limits, which may have been changed as a result of a breakdown of the train ahead, for example, to obtain a new set of speed and thrust-braking profiles for the rest of the transit. These updated profiles are then followed until the next update. Such updating would guarantee getting to the terminal point B nearly on time, but with slightly less than optimal energy cost. It is a matter of experimental test, however, to determine how accurately such a calculation can be made under the current capability of cab signal systems.

INTEGRATED DISPLAY FOR THE HUMAN DRIVER

Although automatic control can relieve the human operator from tedious repetitive manual tasks, it is not always readily accepted for various technical, safety, or political reasons. If automatic speed control is not acceptable, the optimal solution discussed in the previous section can serve as a decision aid for the driver instead. One design of such an aid is the integrated color display shown in Figure 2 in black and white.

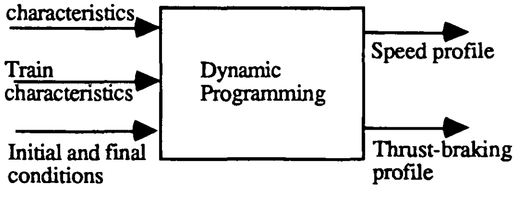

FIGURE 1 Function of dynamic programming algorithm.

This display integrates all relevant information on speed control. It provides the human driver with the optimal thrust-braking profile as a function of train position and tells the driver exactly what control action to take in order for the train to follow the speed profile that meets all the given speed limits, gets the train to the next station or a known terminal point on time, and minimizes energy consumption. The right-hand edge of the speedometer indicates the location of the train momentarily. Atop the speedometer, two horizontal bars might serve as a trip timer and a trip odometer, respectively. The display may also show the stopping distance momentarily. This may help the driver to make decisions on the type or amount of braking force to use in case of track obstruction.

In practice, it is unrealistic to expect a train to follow the optimal speed profile even if the driver follows the displayed optimal thrust-braking profile perfectly. A major reason is that the model used in calculating the optimal solution may not conform precisely to the reality. An example is that the resistance force in the model may not represent that induced by instantaneous wind gusts. One way of remedying this situation is by updating the optimal solution for the rest of the transit, as mentioned in the previous section. Using the deviation of the current speed from the optimal speed, the current time from the scheduled time, or both, as a cue, the driver may request the computer to update the optimal solution. As a result, the control is suboptimal in practice.

TO KEEP OR NOT TO KEEP THE HUMAN DRIVER?

Two contrasting ways of applying an energy-optimal solution to train speed control have been described. It is argued that, under the assumption of sufficiently accurate models of track geometry and train dynamics, and sufficiently accurate train state measurements, optimal automatic control of train speed is feasible. One design of such automatic control would be the direct implementation of the optimal thrust-braking profile described in this paper. Alternatively, the optimal profile can be used, not for automatic control, but as a display for a human driver. If the human, in manual control, followed precisely such a profile, better speed-control performance would be achieved than if that person had to perform various mental calculations during continuous decision making and control. This decision-making process can be quite demanding for a new driver. Thus there are four options:

- *Manual control, with traditional displays only.* Keep the human driver in charge and withhold the integrated display, because he or she might slavishly follow its recommendations and lose the ability to think for himself or herself.
- *Manual control, with the integrated display as an aid.* Keep the human driver in charge, provide the display, and expect the driver to use the display as a decision aid for controlling the train along with his or her expertise.
- *Manual control, with the integrated display as an aid, plus the automatic control option.* Keep the human driver in charge, provide the display, and make some form of optimal automatic control available. Leave the use of either mode of control at any time up to the human operator (much as cruise control is now used in trains and automobiles).
- *Fully automatic control with emergency-override options.* Automatic optimal speed control under normal conditions, but

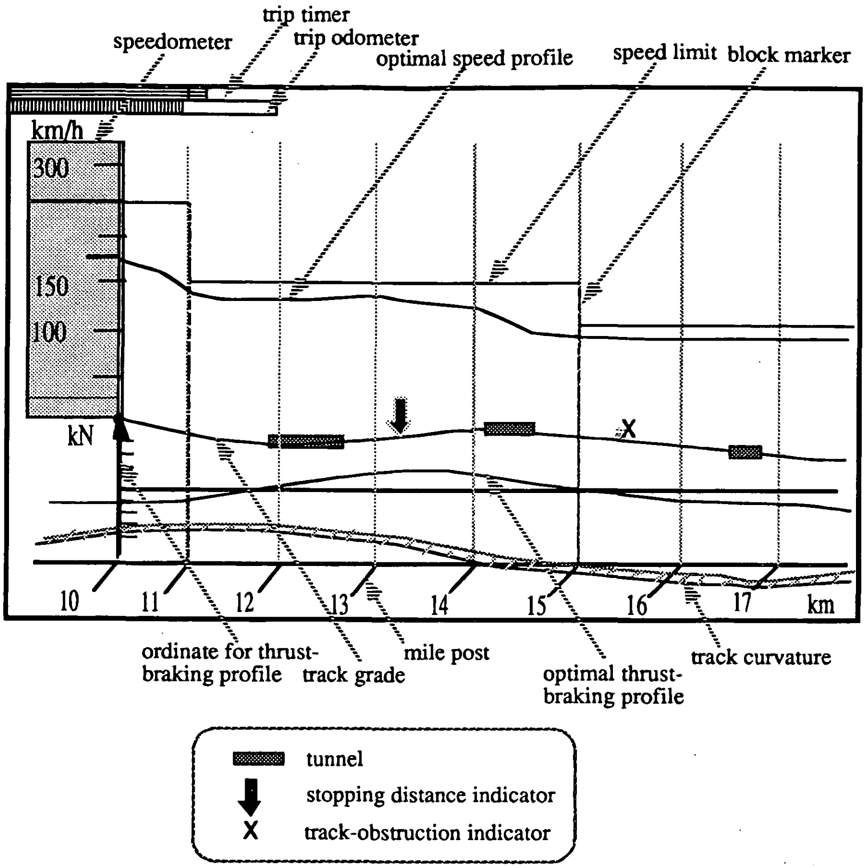

FIGURE 2 Integrated display as decision aid for train speed control.

allowing emergency override by (*a*) an operator in the cab who is there to perform other duties, (*b*) staff personnel elsewhere on the train who might take control from where they are or move to the cab as time allows, or (*c*) a dispatcher from the dispatching center, if the system allows.

Note that these options should include the automatic train protection capabilities with which a train is normally equipped (*3*).

In the fully automatic control mode, the display serves as a means for the computer to communicate with the human driver about the current states and future intentions of the automatic control system. Several considerations bear upon the choice among the speed control alternatives:

- *Basic system features.* System features, especially signal system capability and types of braking systems, strongly influence the appropriate level of cab automation and the role of the driver.
- *Experimental results.* Most important is the outcome of experimental tests and demonstrations of the proposed driver aid or of automation.
- *Proper view of human role in automation.* A prevalent position taken by engineers is that automatic control is essential for modern high-speed trains and there is simply nothing to debate. A high degree of automation is now widely accepted in aviation by pilots, airlines, and regulators, although human pilots remain in cockpits. However, accidents, for which pilots often blame automation, still occur.

With regard to automation, history has shown that we are not always as smart as we think we are. For example, Charles Stark Draper, the father of inertial guidance used to take the astronauts to the moon, proclaimed at the outset of the Apollo Program that the astronauts were to be passive passengers and that all the essential control activities were to be performed by automation. It turned out that he was wrong. Many routine sensing, pattern recognition, and control functions have to be performed by the astronauts, as do some critical emergency decisions.

- *Introduction of new tasks for the human driver accompanying the automation.* Since some tasks (such as planning ahead, replanning in case of emergency, voice communication with the dispatcher, etc.) may not be automated, a trained human operator may be required to remain in the cab, with little to do during normal operations. This may result in loss of vigilance and development of complacency. A natural remedy is to give the operator something more to do. More activity than now practiced in diagnosing various subsystems on the train, such as air conditioning, engine operating status, and the like, is one possibility. How such additional tasks interact with the speed control task is an issue to be investigated.
- *Public anxiety.* It is expected that there would be great public anxiety with driverless control in full-size high-speed trains. However, it is clear that some small-scale trains that operate in airports (e.g., in Dallas–Fort Worth, Atlanta, Orlando, and Chicago) or from airport to city center (e.g., the French VAL) are driverless. Therefore, reflex anxiety about driverless trains may be waning.

- *Liability in case of an accident.* The threat of litigation in case of any accident in an automated system gives developers pause.

The authors believe that development should pass from the current situation, fully manual control (the first control option listed at the beginning of this section), to manual control with integrated display as an aid (the second option listed), to manual control with an automatic control option (the third option), and perhaps finally to fully automatic control (the fourth option). This sequence would be the safest and most acceptable route for development and evaluation.

CONCLUDING REMARKS AND FUTURE WORK

An optimal solution to train speed control has been proposed. Potential uses of the optimal solution for automatic control or as a decision aid for human drivers have been discussed. The decision aid may take the form of the proposed integrated display. It is not the purpose of the paper to provide answers to the design of the cab, but instead to propose possible uses of the optimal speed and thrust-braking profiles and possible designs of a decision aid for the human driver. The authors are in the process of setting up human-in-the-loop simulation experiments to investigate the proposed options. The experiments are expected to provide insight on the issue of human-machine allocation of high-speed train operation tasks.

Although the research is primarily concerned with high-speed trains, the concept proposed in this paper is equally applicable to other types of trains.

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