RECEIVED
MAY 11 1998
OSTI

SAND--98-8541C
CONF-980001--

SERVICE- AND ENERGY-RELATED OPTIMIZATION OF ADVANCED AUTOMATIC TRAIN CONTROL

S.P. Gordon
Sandia National Laboratories
MS 9201, P.O. Box 969
Livermore, CA 94551-0969
voice: (510) 294-3634
FAX: (510) 294-1559
email: spgordo@sandia.gov

D.G. Lehrer
Bay Area Rapid Transit District
212 - 9th Street, P.O. Box 12688
Oakland, CA 94604-2688
voice: (510) 287-4725
FAX: (510) 287-4751
email: dlehrer@bart.dst.ca.us

MASTER
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

The Bay Area Rapid Transit (BART) system, in collaboration with Hughes Aircraft Company and Harmon Industries, is in the process of developing an Advanced Automatic Train Control (AATC) system to replace the current fixed-block automatic system. As in the current ATC system, the trains will be controlled by station computers at the wayside; however, spread-spectrum radios rather than track-circuits will be employed to determine train locations and reliably transfer control information, allowing for finer speed and acceleration control, as well as more precise train locating capabilities and moving-block control. In the long run, the AATC system is expected to not only allow for safe shorter headway operation, but also to facilitate coordinated train control for both smoother service and improved energy management. We have developed a simulator of the train control and power consumption of the AATC system, and are now employing this tool to develop enhanced train control algorithms to supplement the safety-critical controller. These algorithms do not attempt to globally optimize the control system with respect to a cost function, but rather they modify the baseline vital control to smooth out train trajectories, and to reduce energy consumption and power infrastructure requirements, through coordination of multiple trains. Several control algorithms are under development, including (1) delay recovery, which smoothly and efficiently controls trains approaching and stopped behind a delayed train, (2) interference management, which controls closely-following trains to avoid oscillatory brake/acceleration cycles, and (3) low voltage avoidance, which limits power consumption by multiple trains in an area to prevent low voltage events. We will discuss progress to date on development of these control algorithms, as well as their service- and energy-related benefits.

INTRODUCTION

As the BART system expands its service area with extensions to the lines in the East Bay, increased capacity is required to funnel all of this additional traffic through the tunnel under the San Francisco bay and through the downtown. Short of a massive engineering project to add additional track infrastructure in parallel with the current line, closer train headways are required to meet the expected capacity requirements with the existing infrastructure. The current train control system, which is based upon train locating and control from wayside station computers through fixed block track circuits, is reaching the limits of its capabilities. In order to increase the capacity of the system much further, a new system is required.

The AATC system currently under development at BART is expected to fulfill this need through more precise train locating and control. The AATC will employ the Enhanced Position Location Reporting System (EPLRS), a spread-spectrum radio ranging technology developed by Hughes and capable of simultaneous train tracking and communication.(1) Trains will communicate from on-board radios through a network of wayside radios to station computers, which will control the trains in local areas through speed and acceleration commands updated every 0.5 seconds. The radios will carry messages including speed commands resolved to every one mile-per-hour, as well as variable acceleration commands. The time-of-flight of the radio messages to and from the trains will be used to determine the train locations to within 15 feet, removing the large position uncertainty of a track-circuit-based control system. In addition, moving control blocks will be determined based upon the trains' locations, allowing minimum following distances limited only by the required safety considerations.(2)

In addition to fulfilling the immediate need for shorter headway operations to increase capacity on the BART system, the AATC will also be able to take advantage of its wayside control architecture and fine control of train trajectories in order to improve service, as well as

accrue energy-related savings. The control logic of AATC is resident in wayside computers, which calculate speed and acceleration commands for all trains within their control zones. Thus, it is possible to coordinate the motion of multiple trains in order to improve service reliability and passenger comfort, while reducing energy infrastructure and usage costs.

The commands which will be sent to the trains from the wayside will be generated by a combination of two computers -- a vital and a non-vital processor. The vital processor will be responsible for generating safety-critical train speed and acceleration commands and communicating commands to the trains. The non-vital processor, working in parallel, will add enhancements to the baseline vital control in order to meet non-safety-critical objectives such as reliable service and reduced energy usage. This processor will receive information about the states of trains in its control zone from the vital processor, as well as information about trains in neighboring zones through an ethernet connection. When a change to the baseline train behavior is desired, the non-vital processor will pass suggested train control commands to the vital processor, which will then use these suggestions to modify subsequent commands.

In a recent paper, we have described several possible types of non-vital algorithms which are under consideration as enhancements to the AATC system: low voltage avoidance, peak power limiting, interference management, backup recovery, coordinated starts and stops, power-limited acceleration, and coasting.(3) This paper will discuss three of these enhanced control algorithms which are currently under development.

AATC TRAIN AND POWER SIMULATOR

The enhanced algorithms are being developed and tested in the AATC Train and Power Simulator (ATAPS), which simulates the train control and power systems on a single line of the BART system. The core of this simulator is provided by the Train Control Simulator (TCS), which was developed to accurately simulate the motion of trains, in order to test and refine the AATC system before implementation. The TCS provides the capability to simulate different braking and acceleration control algorithms, to estimate run times, and to test changes made to the vehicle control code. The ATAPS simulator supplements the safety-critical control system of the TCS with a non-vital controller, allowing for the addition of enhanced control algorithms for coordination of multiple trains. ATAPS also contains a steady-state traction power model, which allows analysis of power-related metrics, such as energy consumption and low voltages. In its current version, the trains are modeled over the entire length of a single line, whereas the power model extends only over a subsection of that line.

As the simulator runs, it generates output files which record detailed train trajectory and power-related data as functions of time. These data allow for detailed analyses of the impacts of various control algorithms. In addition, the Benefits Assessment Module evaluates a small set of overall power- and control-related metrics, such as the number of voltage sag events, so that the user can easily assess the overall impact of an algorithm without looking at the detailed output data. We believe the ATAPS simulator provides a powerful testbed for development and testing of novel train control algorithms in the context of both train motion and power consumption.

Train Control Simulator

The BART Train Control Simulator is unique in that it incorporates the actual vehicle-borne control code into the train motion calculation. This produces extremely accurate, high resolution simulation data, down to 36 millisecond intervals. With the aid of this precise simulation, BART has further optimized its existing vehicle control system, which had gone unmodified for nearly a decade. The simulator has developed into a key technique in the

validation of such modifications, allowing for more exhaustive testing than might otherwise be possible. Although the use of vehicle-borne code makes the simulator BART-specific, the design is modular enough to allow alternate or more generic train motion code to be swapped in. Future versions of the simulator may be able to select from multiple vehicle types as easily as clicking on a pull-down menu.

The accuracy of the simulator has always been a paramount design concern. To date the TCS has been validated against system-wide revenue service data collected by BART's Central Control System computer, and against data collected during the first phase of AATC system testing. Both have indicated that the simulator precisely models the control and movement of BART trains.

Simulator Features and Design

The TCS has many user definable parameters. It is capable of simulating conventional track circuit-based control systems as well as moving block systems, or a mixture of both. Multiple trains may be simulated simultaneously, each with its own configuration; length, weight, performance profile, and speed selection algorithm are all user definable.

The type of output data and its resolution in time are also user definable. Reports may be generated which log events, such as track circuit occupancies, switch and gate movement, as well as relative position graphs depicting the proximity of trains to one another. All output data is available in ASCII text format.

The majority of the simulator is coded in C and C++. The vehicle control code modules are coded in 80x86 assembler. The program is constructed in modules which functionally represent the train control system elements that they simulate. For example, there are C++ classes which represent the track, the interlocking control system, the station computer and the trains themselves. This modularity allows different subsystem designs to be tested by swapping classes within the simulator.

Figure 1 depicts program flow among the major subsystems within the simulator. The external wayside simulation loop includes all user input functions, speed code generation and output logging. The timing of this loop is adjustable, depending on the control interval and data resolution required.

The internal vehicle control loop includes the actual vehicle-borne control code and motion equations. This loop operates at fixed 36 millisecond intervals, to replicate the design of the vehicle code. Future enhancements to the simulator may include the ability to adjust this time interval as well, allowing more complex track layouts and more trains to be simulated in less time.

Control System Validation and Optimization

Many potential problems have been revealed using the simulator, some far sooner than they might otherwise have been discovered. Early on in the AATC project it was found that trains were routinely undershooting their target brake rates; that is, trains were braking too hard, often by as much as 10%. Investigation revealed that a software module called the Proportional-Integral (PI) Controller, which is part of the onboard vehicle code, contained parameters which were not set optimally. In addition, the code contained a sequencing flaw.

Figure 2a shows a simulated train making the transition from propulsion into braking with the old control code. It is clear that the train's acceleration rate, shown in the accelerometer plot, initially undershoots the commanded rate. Figure 2b shows the same scenario with the new

control code. The simulator facilitated the discovery and correction of this problem. Over time, such small optimizations can add up to substantial savings.

Later in the AATC project, the simulator revealed that a cyclical behavior could result if two trains that had stopped close together attempted to accelerate up to speed. During acceleration, the following train would be forced to repeatedly stop accelerating, and sometimes begin braking, in order to maintain a safe distance from the train ahead. This phenomenon is rooted in the calculation of safe stopping distance, which is proportional to the velocity squared. If the following train accelerates at the same rate as the lead train, its expanding stopping distance quickly overtakes the lead train, and it must stop accelerating. Once its following distance increases sufficiently, acceleration resumes, and the process is repeated. In simulation, this cycle was repeated approximately every five seconds throughout the acceleration profile. Based on the forewarning provided by the simulator, enhanced control algorithms were developed to prevent this oscillatory scenario by continuously adjusting the acceleration rate of the following train to maintain the required following distance.

Demonstration of AATC Capabilities

The simulator has proven to be an invaluable tool for the prediction of overall system performance capabilities. Using the simulator to model the new AATC moving block control system and comparing the run times with simulated track circuit-based control, an estimate of potential run-time improvement was derived. This improvement indicated that entire trains may be eliminated from future schedules, thus reducing operational and capital costs. In addition, the simulator indicates that AATC will be capable of much shorter train headway, allowing for faster recovery after delays.

In addition, the simulator enables comparison of the new control system to the present fixed-block control system. For example, the braking profile of a train traveling through a series of reduced speed limit zones on its approach to a station stop is shown for the two systems in Figure 3. The fixed block system, with its course speed command control and constant-speed-command blocks, forces the train to perform a "stair-step" braking profile. The finer control of the AATC allows optimization of the braking profile, leading to a shorter trip time, reduced energy usage, and, not inconsequentially, a more comfortable ride.(2)

Traction Power Simulator

The traction power model, Modrails (Model of DC Rail Systems), uses the location and power consumption or regeneration of each train at a given moment to calculate the voltage at each train and substation, as well as the power being produced by each substation. The system solution is found in the steady state, so Modrails does not support studies of transients or instabilities in the power network. The primary utility of the model is in evaluating the severity of voltage sags and the usage of regenerated traction power. This model was originally developed in order to analyze the relative merits of an energy storage unit to prevent voltage sags in the transbay tunnel.(4)

The power demand of each train is first calculated by the train Power and Maximum Acceleration Model (PMAM) within the TCS. This module calculates the power consumed or regenerated by a train, and the maximum possible acceleration which the motors can provide given the current train state. This function not only impacts power calculations, but also limits train trajectories to physically realizable accelerations.

Given the calculated power consumption and location of each train on the line, Modrails translates all infrastructure and train information for a linear section of track into a DC electrical

circuit. Incorporated into this model are substation, crossbond, and gap breaker locations derived from the BART track plans. Crossbonds are connections between the running rails in the two directions of travel, and gap breakers are connections between the two powered contact rails. Each train is treated as two separate power sinks (or sources) consuming (or regenerating) half of the total train power, one located at the head of the train, and the other at the tail. This avoids overestimating voltage sags by realistically distributing the power load. Train voltages are limited to a maximum of 1150V during regenerative braking. Power is allowed to flow out of substations onto the third rail, and from running rails into grounds, but not in the reverse directions. Rail resistance may vary in discrete sections, which allows accurate modeling of the presence of low resistance contact rail in some sections of track.

Figure 4 contains sample train- and substation-related output data produced by Modrails during a typical simulation. Train location, speed, command speed (dashed), acceleration, command acceleration (dashed), power consumption, and voltage are shown as functions of time. This train begins at a station, accelerates up to speed, and then decelerates for the next station stop. The commands shown do not match the trajectory during the station-stop, because the final braking for stations is controlled on-board rather than by AATC commands from the wayside station computer. Ultimately, it is expected that the entire train trajectory including station stops will be commanded from the station computers.

In general, while the train is accelerating, power is consumed and the train's voltage drops. When the train is regeneratively braking, the voltage floats up to a maximum of 1150V. Additional trains in the area add complexity to the voltage solutions. The power produced by the substation as a function of time, as well as the substation voltage, is also shown. Power may only flow out of the substation, so power is always positive. When trains are regenerating nearby, the power drops to zero, and the voltage can float up well above the nominal 1050V.

ENHANCED CONTROL ALGORITHMS

The ultimate goal of enhanced train control is a system optimized with respect to a well developed and complete cost function. This function would represent the relative value of such things as trip time, energy and power usage, delay time, and rider satisfaction. Although global optimization is a worthy goal, we believe that it is important to begin tackling the problem of enhanced train control by first solving more localized and well-defined problems. Therefore, we are attempting to design a few control algorithms which solve specific problems, and assessing tradeoffs in their impacts on various important metrics. Once some intuition has been developed in this way, it may be possible in the future to design a more globally applicable algorithm.

Before discussing the specific algorithms that we are pursuing, it is worth noting a general principle that we have noted repeatedly during our pursuit of a more efficient and reliable control system. Our primary objectives for enhanced control include reduced energy infrastructure costs, reduced overall energy usage, and improved service reliability. Fortuitously, in most cases the algorithms developed to achieve these goals provide the additional benefit of improved passenger comfort. For example, in the case of interference during acceleration described in "Control System Validation and Optimization" above, the enhanced control algorithm which enforces a lower acceleration rate saves energy, prevents unnecessary mode changes from braking to acceleration, thereby reducing wear-and-tear on the motors and improving reliability, and at the same time produces a smoother, more comfortable ride. Similarly, the algorithm designed to recover from delays discussed below prevents unnecessary motor mode changes, and can prevent extreme voltage sags if the delay occurs in an area with limited power availability. In the process, this algorithm also makes delay-recovery a less

noticeable event for the passengers. In general, both energy and reliability goals are linked to smoother train trajectories, which are more comfortable to experience as well.

Delay Recovery

As trains are scheduled closer together in order to increase system capacity, delayed trains can become more and more of a problem. The vast majority of delays on the BART system have a duration of less than four minutes. As scheduled headways on the system are reduced to two minutes or less, delays which are currently unimportant will cause backups unless enhancements are added to the control system. With this in mind, an algorithm has been developed which will handle such delays more smoothly.

When a train stops outside of a station, the algorithm recognizes that a delay has occurred and calculates reduced speed commands for any approaching trains in order to prevent them from stopping. If the delay continues for a prolonged period, some trains will eventually be forced to stop in a backup behind the delayed train. When the delay finally does begin to move, the algorithm staggers the starts of any stopped trains so as to avoid simultaneous acceleration which can lead to power spikes and voltages sags. In addition, approaching trains are controlled so as to arrive as the backup clears. If additional delays occur in the station, then the algorithm reduces the speeds of all approaching trains accordingly so that trains will not be forced to stop. As long as additional delays are on the order of 20 seconds or less, this approach is successful. However, a substantial delay to a second train can cause a backup to recur. In this case, the algorithm will reset itself and begin again as though this were a new event.

Figures 5a and 5b show the results of simulation runs in which a train is delayed in a station for 400 seconds. Trains are approaching the backup at 120 second intervals. The graphs show the full length of each train as a shaded region along the location axis. The trajectory is flat when a train is stopped, and sloped when it is in motion. The backup moves through the station with nominal control in the first figure, and with the delay-recovery algorithm in place in the second figure.

Under nominal control, several trains stop behind the delayed train during the delay. Even after the lead train begins to move, additional trains continue to arrive and stop behind the backup. As the backup clears, the line of trains moves forward one train length at a time as the trains pull out of the station. This behavior leads to spikes in power demand, as the trains repeatedly accelerate and then brake to a stop. In addition to the resulting frustrating ride and the waste of energy, low voltages may result if sufficient power is not locally available for multiple accelerating trains.

With the delay-recovery algorithm in place, the same event causes only two trains to stop during the delay, and no further stoppages occur thereafter. The headway at departure from the station is maintained at approximately 80 seconds, which matches the headway achieved by the nominal stop-and-start approach. In addition to the delay at the station shown in the figure, this algorithm can handle delays in any location before the station, again reproducing the short headway on station departure of the nominal control system but without any unnecessary stops before the station stop.

Not only does this control technique provide obvious improvements in passenger comfort and reduced wear-and-tear on the motors from mode-changes, it also accrues power-related benefits. For a 500 second delay in the middle of the BART transbay tunnel, where there is insufficient power available for more than one or two trains to accelerate at once, nominal control results in a severe voltage sag. In simulation, the train voltage drops repeatedly to the point where train motors would shut down to avoid arcing due to excessive motor current. On

the other hand, the voltage remained above 800V with the algorithm in place to stagger the starting times of the trains. Avoiding voltage sags not only prevents motor shut-downs, but also saves energy. For the same backup in the tunnel, enhanced control saves 8% of the energy used compared to nominal control by reducing the energy losses in the rails associated with low voltages.

Interference Management

Interference occurs when trains run so closely together that they are forced to brake in order to maintain sufficient following distance. An interference management algorithm is under development to avoid oscillatory brake/acceleration cycles due to interference, and, in general, to smooth the trajectories of closely-following trains. This is achieved by maintaining sufficient following distance to prevent unnecessary braking. The payoff from this algorithm comes from reduced energy costs, reduced motor wear, and improved passenger comfort.

When a train follows very closely behind another, it tends to alternately accelerate and then brake as the two trains go over hills, or as they accelerate and brake between stations. As a train travels, it's predicted stopping distance can increase if the average grade in front of the train becomes more down-sloped. If that train is traveling as close as possible to the train in front of it, then it will have to brake if its stopping distance increases. This type of "interference" is predictable and preventable. Similarly, as discussed earlier, when two trains that are close together accelerate up to speed, the stopping distance of the rear train increases due to its increased momentum, and again oscillations can result. Although this behavior only becomes apparent when trains are abnormally close together, such as after delays, it is wasteful of energy, uncomfortable for passengers, and, most importantly, preventable. Like delays, this "off-normal" condition will become more the rule than the exception as the scheduled headway becomes shorter to meet additional demand.

An enhanced control algorithm can manage interference by maintaining a following distance which is greater than the largest stopping distance expected between a train's location and the next station stop. The stopping distance may be pre-calculated as a function of location and speed, and the maximum predicted stopping distance may then be calculated based on this function. Figure 6 shows examples of stopping distance (dashed) and maximum stopping distance (solid) between two stations as functions of location and speed. If the following distance of a train is maintained at all times above the maximum stopping distance for its location and speed, then braking due to interference will not occur. In order to maintain this separation, when a train is accelerating close behind another accelerating train, its acceleration rate will be calculated such that its following distance increases to match its maximum stopping distance. If a train is following another train that is not accelerating but is traveling slowly, then the rear train will slow to match speeds with the lead train when it is following at its maximum stopping distance.

In addition to interference due to changes in stopping distance, avoidable braking may result when trains are close together in a region with closely-spaced stations. If a train is stopped in a station, and another train approaches, the second train will begin to brake early to stop short of the station. If the train in the station then pulls away, the rear train may accelerate briefly before stopping for the station. This sequence may then be repeated at each station along the line if the stations are close together, as is the case in downtown San Francisco. A relatively simple algorithm is capable of removing this type of interference. If a train is braking before a station because a train is stopped there, and it is then freed to accelerate by the stopped train pulling out

of the station, then it should only accelerate if it would add excessively to trip time to remain in braking. Otherwise, it should continue braking at a low rate until the station stop.

Figure 7 shows an example of a train trajectory exhibiting interference before two consecutive stations. The velocity of the interfered train is shown as a function of time, as calculated by the simulator with and without enhanced control. At the expense of a few seconds of trip time, the enhanced trajectory is smoother, again saving energy and improving passenger comfort. The trip time increase shown here may be reduced by enforcing a stricter time limit, which in this case would cause the train to accelerate to the first station, but to remain braking to the second station, where very little trip time is added.

Low Voltage Avoidance

Even with a power infrastructure that is sufficient to run trains normally the vast majority of the time, occasional coincidences of multiple trains accelerating may still cause the voltage to drop to unacceptably low levels. Low voltages can cause trains to run at reduced performance levels, or even to shut down in order to avoid damage from excessive current flow. Even with motors that do not shut down, it is inefficient to allow severe voltage sags, as low voltages typically correspond to large power losses. The typical response to this situation is to add more power infrastructure until the system is sufficiently robust as to be able to handle any possible situation which may occur under relatively normal operating conditions. Moreover, since the system must be able to operate during an outage at a substation, additional power capacity must be installed so that the voltage will be maintained at some reasonable level even in this circumstance. Enhanced control can avoid low voltages by regulating power usage, thereby avoiding, or at least deferring, tens of millions of dollars of traction power capital equipment costs.

In order to maintain the voltage of all trains above some reasonable minimum, which would be somewhere in the neighborhood of 800V, it is necessary to predict train voltages based upon the trajectories of all nearby trains, and then allocate the available power in such a way as to maintain the voltage at all trains while minimizing the impact on the schedule. This algorithm, with such a high payoff, is not surprisingly the most difficult to achieve. Train voltage is a non-linear function of power demand, which makes it difficult to predict quickly and reliably. In addition, power consumption can rise quickly enough to take the voltage from a comfortable range to well below the desired minimum in a matter of seconds. Thus, it is not sufficient to measure or calculate train voltages and react as the voltage drops too low; but rather, potential problems must be recognized before they materialize.

Rather than employing a slow but accurate system model such as Modrails to predict voltages, we are attempting to employ neural network technology to estimate voltages. Data produced by multiple simulator runs are being used to train a neural network to predict train voltages based on local power demand patterns. We have had some success in the pursuit, and this method shows promise. With a neural network to provide a functional approximation of the system, an algorithm may then calculate reduced acceleration commands for trains so that the predicted voltage will never drop excessively. As a future enhancement, train voltages could be measured on the system real-time, and this data could be used to continue to train and refine the neural net to improve its accuracy, and thus to increase the effectiveness of the algorithm over time.

It is possible that a better solution to low voltage problems may be achieved through on-board rather than wayside control, because this would avoid the problem of predicting low voltages and mastering the time lag between wayside command and execution. However, if it is

possible to solve these problems of wayside control, then this approach allows for more flexibility in the way that limited power resources are allocated. For example, on-board reaction to low voltages would be reduce the power demand of all trains based solely on the voltage measured on-board that train. By contrast, a wayside controller could take into account the schedule, and prioritize the power allocation to various trains based upon their priority. If two trains traveling in opposite directions on a line are both accelerating, and there is only sufficient power available for one of them, then the on-board control solution would be to cut the power demand of each in half. However, if one train is on time, and the other is critically behind schedule, then it may be desirable instead to allocate most of the power to the high priority train and allow the other to coast. A wayside controlled algorithm would allow such decisions to be made on a case-by-case basis.

CONCLUSION

Development of a simulator of the train control and traction power systems at BART has been beneficial in assessing the benefits of conversion to a moving block control system from the present fixed block system. In addition, it has proven to represent an invaluable tool for developing and refining the control system before implementation, and for tracking down potential problems in the control system while it is still being designed.

The new Advanced Automatic Train Control system will allow not only more precise control of trains, but also coordination of the commands to multiple trains. Enhanced control algorithms will be incorporated into the system in order to reduce energy capital and operating costs, while simultaneously improving passenger comfort and equipment reliability.

ACKNOWLEDGMENTS

The authors are indebted to Timothy Sa for valiantly integrating two disparate computer simulators into one. They are also grateful to Richard Wheeler, Gene Nishinaga, and John Evans for many useful discussions. The submitted manuscript has been authored by a contractor of the United States Government under contract. Accordingly the United States Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for United States Government purposes.

ENDNOTES

1. G.L. Mayhew, J.A. Kivett, J.G. Himes, and J.A. Evans, "Application of Radio Navigation Technology to Advanced Automatic Train Control," IEEE Position, Location, and Navigation Symposium (p. 217), Las Vegas, Nevada, 1994.
2. E. Nishinaga, J.A. Evans, and G.L. Mayhew, "Wireless Advanced Automatic Train Control," IEEE Vehicular Technology Society News 41 (p. 13), 1994.
3. S.P. Gordon and D.G. Lehrer, "Coordinated Train Control and Energy Management Control Strategies," 1998 ASME/IEEE Joint Railroad Conference, April 1998.
4. S.P. Gordon and W.S. Rorke, "Energy Storage and Alternatives to Improve Train Voltage on a Mass Transit System," Sandia Report #95-8222, April 1995.

LIST OF FIGURES

Figure 1. Train Control Simulator flow chart
Figure 2. Simulation of (a) original and (b) revised PI Controller
Figure 3. (a) Stair-step braking versus (b) optimal braking
Figure 4. (a) Train- and (b) substation-related output data

Figure 5. Recovery from a delay with (a) nominal and (b) enhanced control
Figure 6. Maximum stopping distance
Figure 7. Smooth interfered station approach

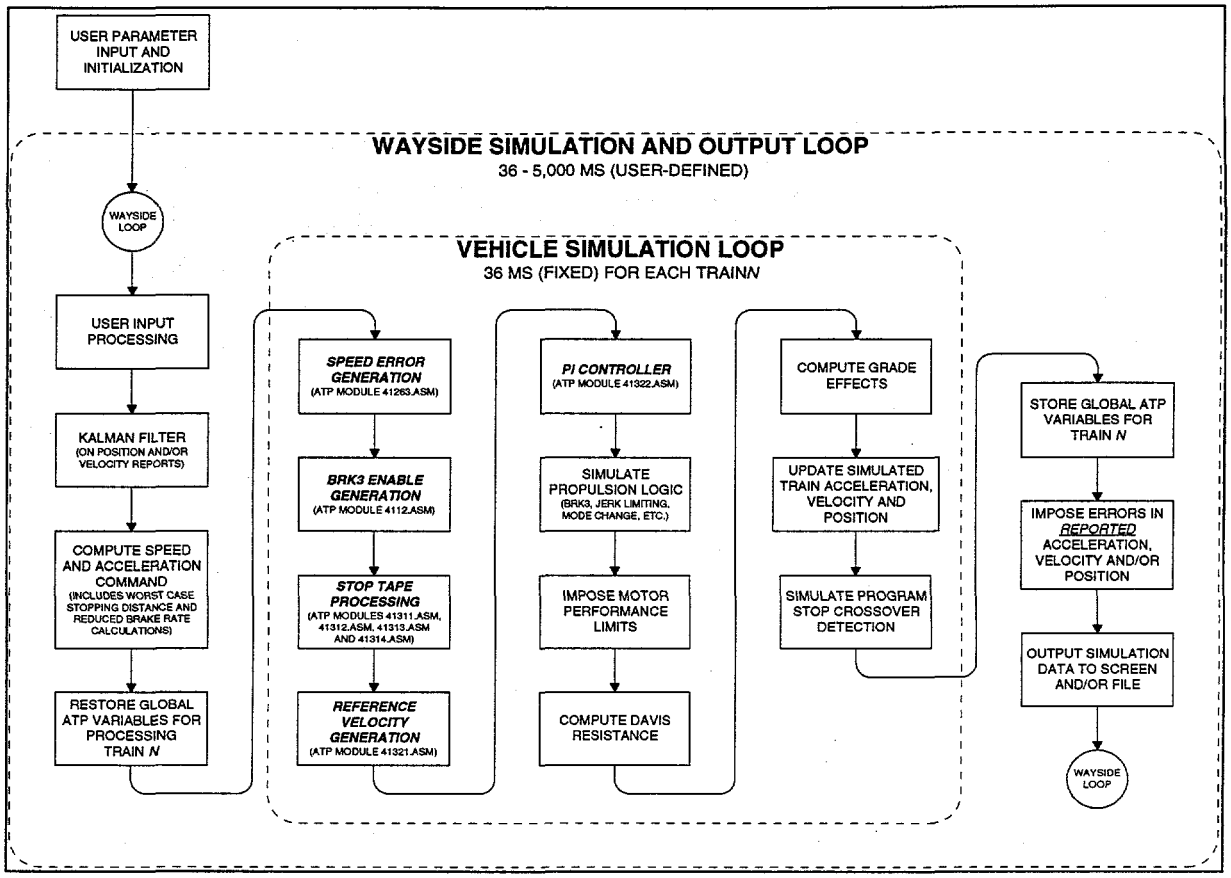

Figure 1. Train Control Simulator flow chart

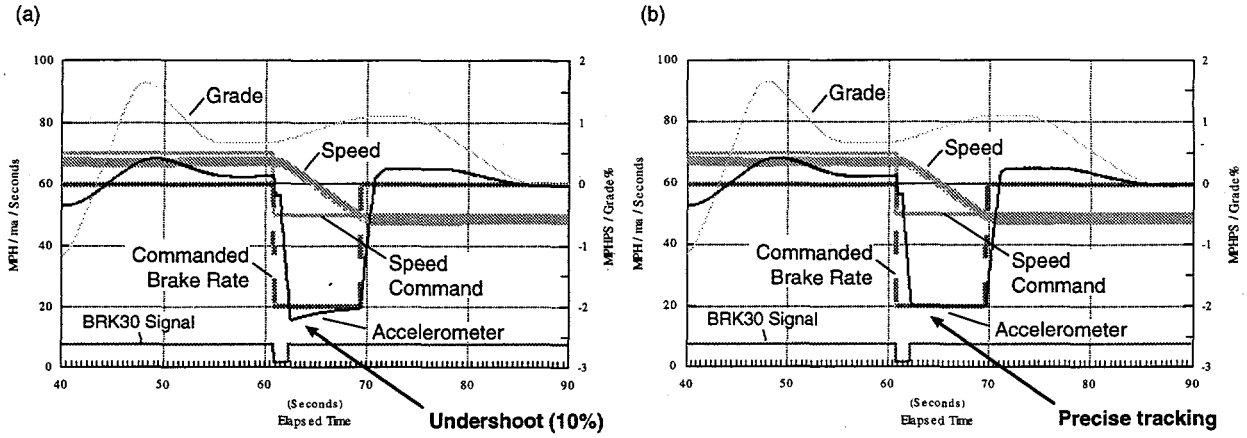

Figure 2. Simulation of (a) original and (b) revised PI Controller.

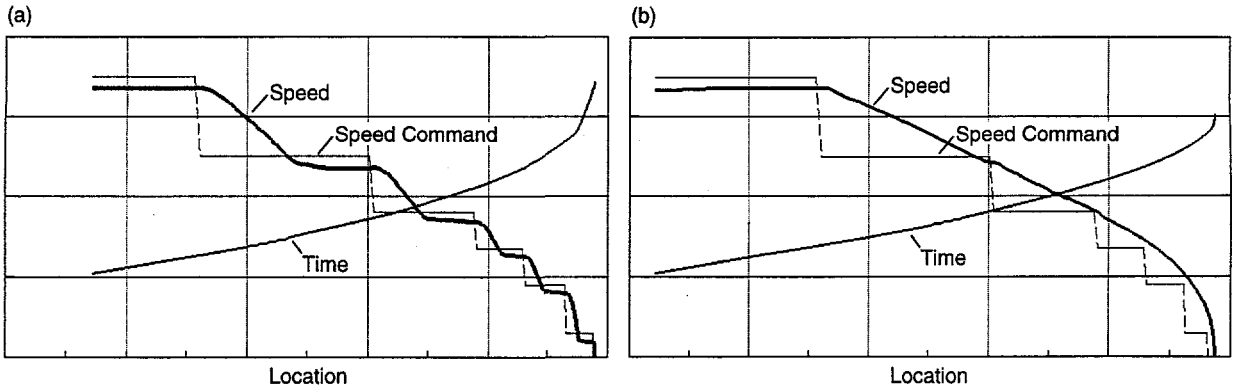

Figure 3. (a) Stair-step braking versus (b) optimal braking.

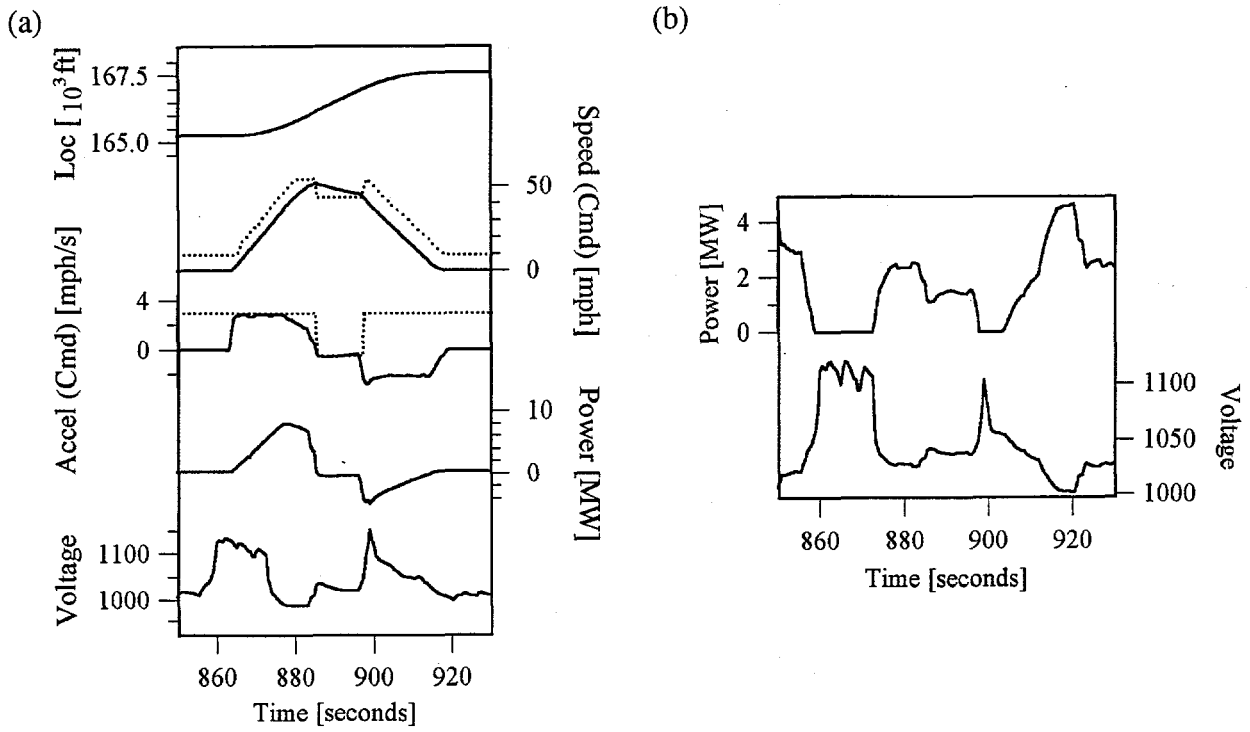

Figure 4. (a) Train- and (b) substation-related output data.

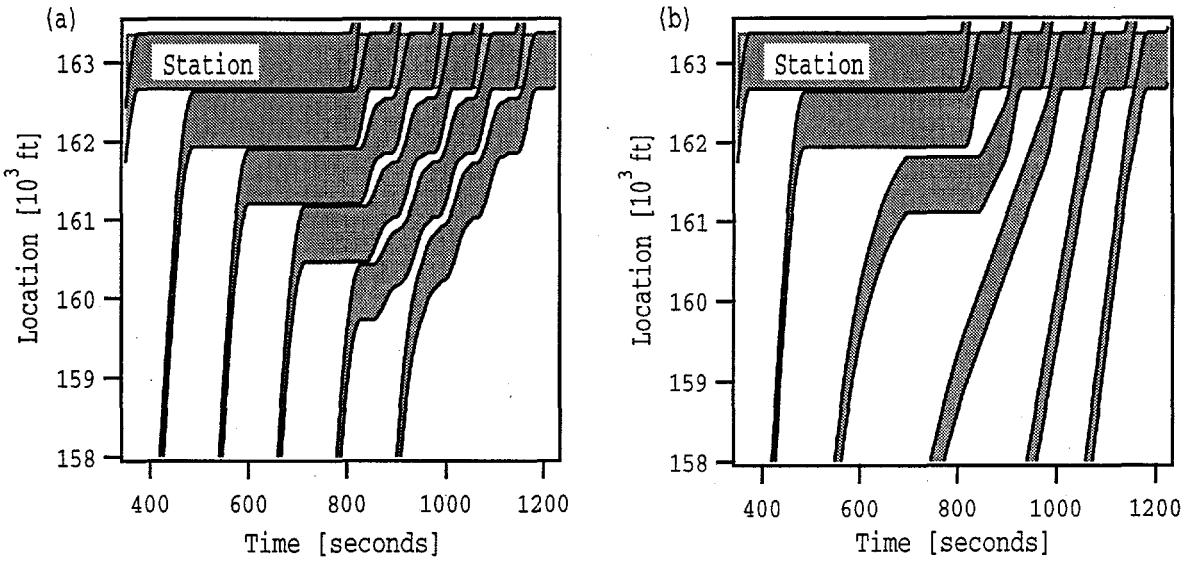

Figure 5. Recovery from a delay with (a) nominal and (b) enhanced control

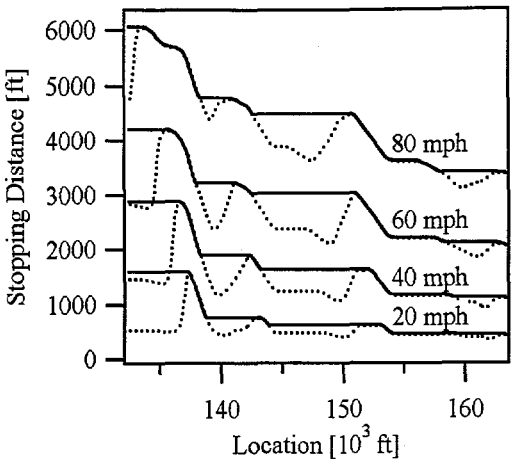

Figure 6. Maximum stopping distance

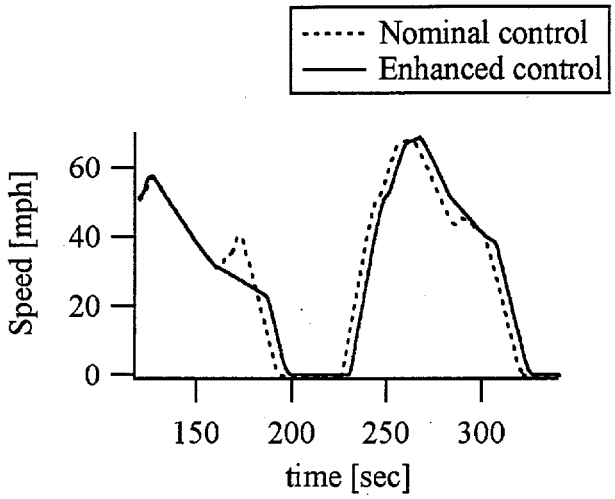

Figure 7. Smooth interfered station approach