AUGMENTED BLOCK GUIDANCE a control concept for automated urban transit

G. L. Pitts and E. J. Hinman

Introduction

Current urban travel is characterized by highly diverse trip patterns, with approximately 70% of all trips being less than 6 miles in length. These random trip patterns have made it increasingly difficult for current forms of public transportation to cope with the needs and demands of the traveler and have created almost complete reliance on the automobile. Therefore, if public transit is to have an impact on urban travel, it must provide a means of accommodating for these travel patterns and providing a service that is comparable to that of the automobile. It is generally agreed that any public transit that is to provide an alternative or supplement to the automobile must provide to the traveler comparable service and trip times at similar cost and with similar personal amenities.

Many new systems have been proposed to perform this service and have been classified as Collection and Distribution (C&D) Systems. The C&D Systems are designed for the circulation of passengers over a limited area, either as feeders to some other system or for local travel. The application of current interest for these systems is for high activity areas such as central business districts, large shopping or office complexes, airports, university campuses, and new towns. These C&D Systems employ small vehicles (6 to 40 passengers) operating at moderate speeds (40 mph or less) and with close station spacing. The mode of operation may vary from scheduled or demand-activated service along a restricted set of guideways, e.g. a closed loop, to a Personal Rapid Transit (PRT) mode, i.e. service to a single or related group of passengers from any origin to any destination without stops within a network of guideways. This latter service is most nearly comparable to that of an automobile.

From an operational point of view, the introduction of C&D Systems implies a need for a large fleet of vehicles operating at headways considerably shorter than in current use in the transit industry. As a consequence, the Urban Mass Transportation Administration (UMTA) is continuing to sponsor a major investigation of command and control concepts capable of providing the necessary management and operational functions.

UMTA-sponsored program activities have been in progress at APL as part of a continuing effort since 1968. In previous phases of the program APL has developed a number of vehicle headway control concepts and has expended significant effort in the area of vehicle management algorithm development. The general function of these investigations has been to map out the major problem areas, thus providing the basis for a definitive program directed toward their solution.

One aspect of the overall command and control problem that has been investigated in detail is concerned with implementation of regulation control laws that vary the speed of individual vehicles as a function of the speed and spacing of the immediately preceding vehicle. This type of regulation approach, usually called vehicle-following, requires a measure of the spacing between vehicles in order to generate the proper speed commands. System headway (intervehicle spacing divided by speed) can be automatically maintained over a range of speeds by proper selection of the regulator gains.

However, regulation of vehicle spacing considers but half the total problem of vehicle control.

Random trip patterns that characterize urban travel pose unique and critical control problems for public transit systems. This paper describes a vehicle control concept that meets the requirements for automatic fail-safe operation of short-headway transportation systems. A discussion of the principal design tradeoffs and constraints associated with this control concept is included. The detailed computer simulation results of the overall control system presented establish the feasibility of this approach to vehicle control.

The other half of the problem is concerned with guaranteeing the safety of passengers in emergency situations. Historically, public transit systems operating on exclusive rights-of-way (e.g. rail rapid transit) have been required to meet very stringent safety standards. Typically, any equipment that could affect the safety of passengers must be designed so that any failure, or combination of failures, in the equipment will cause reversion to a state known to be safe (fail-safe design). Furthermore, the equipment must be so designed and the system so operated as to preclude the possibility of collision between vehicles, even if one vehicle on the guideway fails in such a way that it stops instantly (the so-called "brick wall" criterion). Obviously, such severe constraints on design and operation clearly indicate that for automated transit systems planned for near-term implementation, a conservative approach to the design of safety subsystems is required.

In order to provide assurance that vehicles in a system will not collide, it is first necessary to provide a secure means of establishing and maintaining the appropriate separation between vehicles. In general, two techniques have been considered to provide this function. The most straightforward approach is to have each vehicle perform the measurement of distance directly by onboard equipment. This approach is normally referred to by the term "moving-block." An alternate, indirect method of providing vehicle separation is to perform the detection function from the wayside and transmit the necessary information to the vehicles. In this indirect approach, which is the one used by current systems, the guideway is divided into suitable sections called "blocks" and a minimum number of empty blocks maintained between vehicles.

To assess the state-of-the-art in headway sensing and signal conditioning applicable to short-headway, automated transit vehicles, a subcontract was awarded the Bendix Aerospace Systems Division in 1970. The task assigned was to conduct a survey of the available or potentially available methods of measuring short headways to an immediately preceding lead vehicle. This investigation[1] revealed that, although several alternate schemes had been proposed and a few actually implemented and tested, no technique other than the traditional fixed-block was available at that time that would meet the stringent safety standards imposed.

This result suggested the need for a thorough study of the constraints and capacities of the fixed-block headway protection technique to determine whether this approach was feasible and practical at short headways. The affirmative answer this investigation produced provided convincing evidence that fixed blocks could be used for near-term application of headway protection functions. This evidence, coupled with the inherently discrete nature of digital signal processing, in turn prompted an investigation of the feasibility of using the block signals, generated to assure headway protection, to provide adequate regulatory performance of a vehicle-follower-type control scheme. The control system design that resulted from these investigations, called Augmented Block Guidance (ABG), provides an intermediate step between conventional techniques and total computer control. ABG adapts traditional fixed-block signaling technology to short headway operation by restructuring existing signaling hardware so that it not only provides the required fail-safe headway protection function, but also provides the information needed to precisely control the spacing between vehicles.

Control System Description

A schematic diagram of the ABG control system is shown in Fig. 1. The essential element of the controller is a fail-safe fixed block signaling system that serves as the primary measurement and communication channel. This signaling technique uses a distributed approach that places part

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[1] *Headway Sensing for Automatically Controlled and Guided Vehicles,* APL/JHU TCR 012, Bendix Aerospace Systems Division, Sept. 1970.

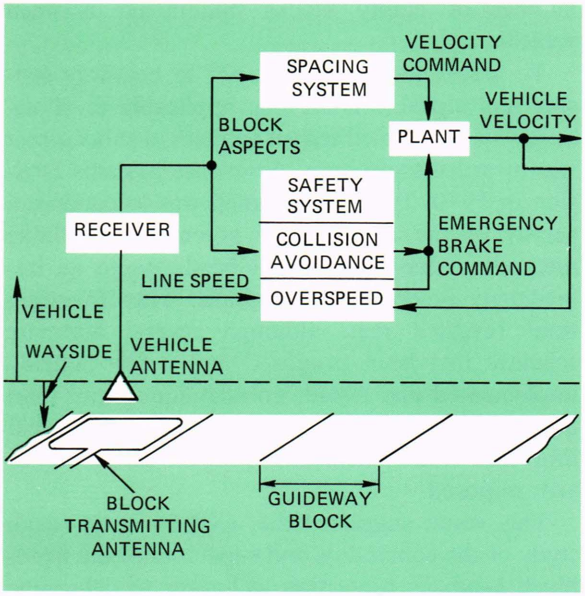

Fig. 1—General block diagram of the Augmented Block Guidance control system.

of the required equipment in the guideway and part in the vehicle. The guideway is segmented into fixed blocks, or distance segments, each instrumented to detect when a vehicle is occupying it. Signals, called block aspects, are transmitted via an inductive link to vehicles as a function of the occupancy of the blocks preceding each vehicle. These signals are decoded by the vehicle and routed simultaneously to each of the two on-board control subsystems.

The safety subsystem continuously checks the integrity of the path ahead of the vehicle. This is accomplished with a simple collision avoidance controller that compares the received block aspect with vehicle speed to assure that a safe stopping distance always exists between the vehicle and the next preceding occupied block. Emergency brakes are automatically applied whenever this safe stopping distance is violated. A second task of the safety subsystem is to guarantee that a dangerous vehicle overspeed condition does not occur. In either task the safety subsystem has priority over all other commands issued to the vehicle.

The safety subsystem assumes vehicle control during an emergency. At all other times the vehicle is under direct control of the spacing subsystem. Two modes of operation are employed. For separations that are long compared to the stopping distance, a velocity controller maintains the called-for velocity with zero steady-state error and little or no sensitivity to changes in wind drag or vehicle loading. At separations close to the stopping distance, a regulation mode is used where each vehicle accelerates or decelerates to maintain the proper spacing between itself and the immediately preceding vehicle. This vehicle-follower concept is analogous to the way automobiles are driven on highways.

Each of the major components of this control system will now be defined in detail.

Collision Avoidance System—The ABG collision avoidance system[2] utilizes more or less conventional fixed block signaling techniques. However, there are fundamental differences in the interpretation of the received aspect signals, in the action taken by the collision avoidance system, and in the restrictions placed on block size.

In conventional block systems, the aspect signal is interpreted as a speed command. The values of the commanded speeds, along with block lengths, are selected to assure that the safe braking distance for a train is less than the distance spanned by the unoccupied blocks ahead. Control equipment on the train automatically accelerates or decelerates the train in accordance with the received aspect signals. Thus, the task of headway protection is combined with that of speed regulation. The specifications of aspect signals and block lengths are based on the local speed limit of the track section under consideration, the local grade, and in some instances the train schedule.

The ABG control approach separates the collision avoidance function from the speed regulation function. The sole purpose of the ABG collision avoidance controller is to apply the emergency brakes the instant the minimum headway is violated. To accomplish this, the aspect signal is interpreted as the number of blocks separating a vehicle from the next preceding vehicle. Since the ABG system only uses blocks of a constant length, the aspect signal is in reality a spacing measurement that has a one-block quantization level. This fact influences the design and operation of the collision avoidance controller.

The collision avoidance controller is designed to meet the safe braking distance headway criterion; that is, it must prevent collisions between vehicles in all possible circumstances, including, if required,

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[2] G. L. Pitts, *A Collision Avoidance Control Law for Fixed Block, Short-Headway Transportation Systems,* AIAA Paper No. 71–942 presented at AIAA Guidance, Control, and Flight Mechanics Conference, Hempstead, N.Y., Aug. 17, 1971.

instant stopping of a failed vehicle. To satisfy this criterion the controller need only control emergency braking effort. A collision avoidance controller located within each vehicle monitors vehicle speed and the block aspect signal. Based on these inputs, the collision avoidance controller makes a decision to either hold the emergency brakes off or apply full emergency braking effort. Once the emergency brakes have been activated, they are not released until the vehicle comes to a complete stop. Furthermore, the emergency brake command has highest priority, overriding any other command of the spacing controller.

The collision avoidance controller implements the decision rule in the hardware. One simple way to implement this controller is with a switching boundary, as shown in Fig. 2. The ordinate represents the received block aspect signal, and the abscissa represents the vehicle speed as measured with an on-board tachometer. The switching boundary divides the aspect/speed plane into two parts: the upper region of the plane corresponds to a safe aspect/speed combination and the emergency brakes are held off; the lower region represents an unsafe and, therefore, forbidden aspect/speed combination. If the system operating point ever crosses the switching boundary, the collision avoidance controller recognizes this as an unsafe condition and applies full emergency braking effort. The switching boundary exhibits the staircase shape because the aspect signals are discrete.

The crux of the design problem is to define the boundary so that the following requirements are met: First (and most important), collisions must be prevented. Second, the block size should be maximized, since the total cost of wayside hardware for fixed-block systems varies inversely with block length. Third, false-alarm braking, which will be discussed later, must be avoided.

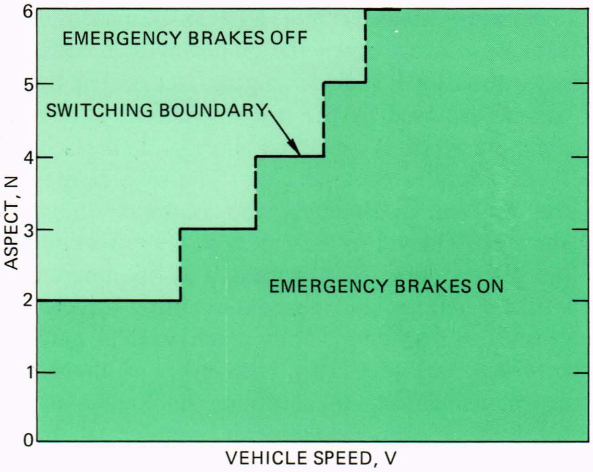

Fig. 2—Collision-avoidance control law structure.

In reports by Pitts[2,3] these requirements are translated into the following analytic constraint equations:

$$B(v)d \geqq X(v) + W \tag{1}$$

$$[B(v) + 1]d \leqq S(v) + W \tag{2}$$

where $B(v)$ is an integer function defining the switching boundary, d is the length of a guideway block, $X(v)$ is the distance required to stop a vehicle from any initial speed v, $S(v)$ is the minimum separation (nose-to-tail) attained during vehicle regulation, and W specifies the mounting locations of the vehicle antennas. Each vehicle has two antennas, the receiving antenna that receives the block aspect signal transmitted from the guideway and a pseudo-antenna, called the presence transmitting antenna, which is the point on each vehicle that is detected by block occupancy hardware. The parameter W is the sum of the distance from the receiving antenna to the nose of the vehicle and the distance from the presence transmitting antenna to the tail of the vehicle.

Equation (1) guarantees that no collisions will occur. $B(v)$ defines the aspect signal that, if received, causes emergency braking. At this instant the separation between vehicles, as measured by the block aspect $B(v)d$, must be greater than the stopping distance. In addition, the vehicle antenna location must be taken into account as specified by W.

Equation (1) is illustrated graphically in Fig. 3, where the quantity $B(v)d$ is plotted as a solid staircase function. The curved line represents the stopping distance function $X(v)$. To prevent collisions, the solid staircase must lie above the stopping distance function for all velocities.

Equation (2) defines the restrictions necessary to prevent false alarm braking. To understand the false alarm braking problem, consider two vehicles moving along the guideway at constant speed and spacing. Because of the block quantization effect, the trailing vehicle alternately receives one of two aspect signals. Now let the block size increase. As

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[3] G. L. Pitts, *Augmented Block Guidance for Short-Headway Transportation Systems*, APL/JHU TPR 023/CP 019, Sept. 1972.

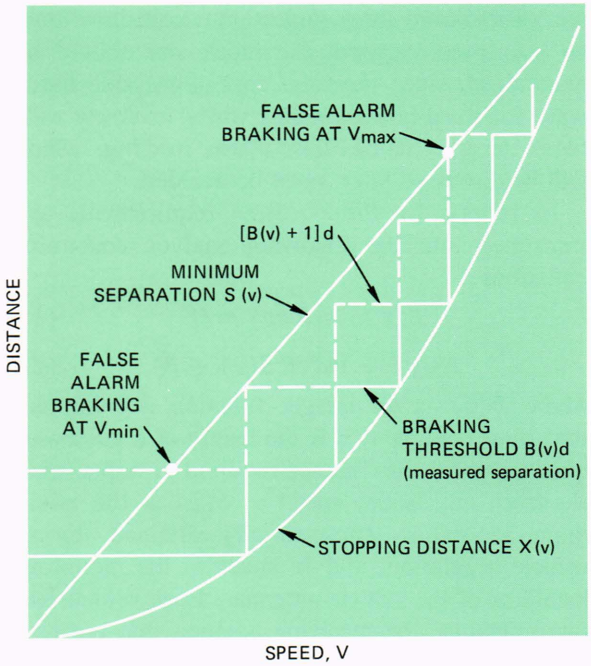

Fig. 3—Significance of constraint equations.

it does, the received aspects become more and more restrictive until the block length d becomes large enough that one of the received aspects triggers the emergency brakes. Thus, even though the spacing is safe, emergency braking occurs. It has been shown[3] that false alarm braking will not occur if the minimum separation between vehicles, $S(v)$, is greater than or equal to $[B(v) + 1]d - W$. Simply stated, Eq. (2) requires that the lowest aspect received during nominal operation be one aspect less restrictive than the aspect that triggers the emergency brakes. This constraint is illustrated in Fig. 3 where the dashed staircase is the quantity $[B(v)+1]d$ and $S(v)$ is shown as a linear function. False alarm braking will be prevented as long as $S(v)$ lies above the dashed staircase (true for all speeds defined by $V_{min} \leq v \leq V_{max}$).

In the design of the switching boundary there is strong interplay between the separation policy used for regulation, the stopping distance function, the operational speed range, and the block length. The problem centers on choosing the largest d that allows the staircase functions in Fig. 3 to just fit between the S and X curves. A design procedure for the optimization of d consistent with Eqs. (1) and (2) has been developed.[2]

In general, this optimum block length follows these basic trends:

(1) Reducing the vehicle stopping distance function (e.g. by increasing the guaranteed emergency braking rate) increases the maximum allowable block size.

(2) Short headways require small blocks. In the limit as vehicles approach a one-stopping-distance separation, block sizes shrink to zero, and continuous sensing is required to prevent collisions.

(3) Spacing control system regulation errors tend to reduce block size because they reduce the minimum separation. Thus, there is a block length benefit to be gained by accurate spacing control.

(4) In most cases, wide dynamic speed range requires reduced block sizes.

Using the ABG approach to collision avoidance usually results in smaller block sizes than those used in conventionally designed block systems, since a constant block length is required on all sections of the main guideway. For example, a block length of 43 feet is needed for a 6.5-second headway system when the stopping distance is computed assuming a 0.27 g emergency braking rate, a 0.4 g/sec emergency jerk rate, and a 0.5-second brake system time delay. On the other hand, this design is optimized for a range of operational speeds rather than a single speed, as required by the conventional approach, and construction costs of the guideway blocks are probably reduced when all blocks are the same length.

There is one other important advantage of this approach. Under the restriction of equal block lengths, simple signal processing can be used to convert the aspect signal into an accurate measurement of the spacing between vehicles, eliminating the need for a separate sensor. In the next section the signal processing will be described.

Spacing Measurement System—Consider two vehicles moving down the guideway at a constant separation of 3.5 block lengths. Let N denote the aspects received by the trailing vehicle. If $N = 1$, the next block is occupied; if $N = 2$, the second block ahead is occupied, etc. The time history of the aspects received by the trailing vehicle is shown in Fig. 4. An increment in the aspect means the lead vehicle has crossed a block boundary, while a decrement means the trailing vehicle has crossed a boundary. Thus, each vehicle may be precisely located during each cycle of the block aspect waveform. In addition, the lowest aspect received defines the integral number of block lengths separating vehicles—in this case, three.

The information contained in the aspect signal

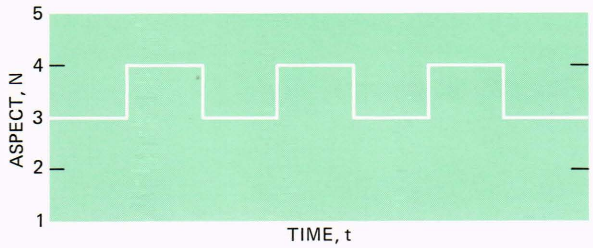

Fig. 4—Typical aspect time history.

can be used if the basic spacing measurement is expressed as:

$$S = (N' + \varepsilon)d, \qquad (3)$$

where S is the spacing measurement, N' is the integral number of blocks separating vehicles, d is the block length, and ε is the fractional block length remaining.

The measurement process consists of identifying N' and ε. Deriving the value of N' from the aspect signal is straightforward. It is just the lower value of the rectangular aspect history and can be extracted with simple signal processing.

Determining the value of ε is only slightly more complicated. As part of the on-board signal processing, assume that there is a digital shaft encoder driven by the vehicle axle and a digital downcounter that accumulates the encoder pulses, each encoder pulse representing an increment in vehicle position. With proper control logic this hardware keeps track of the fraction of a block that must be traveled to reach the next block boundary. To do this the downcounter is reset to a value of one block length each time the aspect signal decrements. Shaft encoder pulses gated to the downcounter subtract the distance traveled by the vehicle as it progresses into the block. Therefore, the contents of the downcounter at any instant represent the distance to the next block boundary. As the vehicle approaches this next boundary, the counter approaches zero, only to be reset again when the vehicle crosses over the boundary.

The quantity ε can be obtained by recording the contents of the downcounter at the instant the lead vehicle crosses the next block boundary. The trailing vehicle detects the block crossing by the increment in the block aspect signal it receives.

The basic signal processing hardware needed to reconstruct both the N' and ε components of the spacing measurements is shown in Fig. 5. The level logic computes N' from the aspect history. The transition-detection logic emits a single pulse on either the increment or decrement output (depending on the sign of the aspect transition). A decrement pulse resets the downcounter to an initial value of 1. When an increment pulse occurs, both latches are strobed and N' data are stored in latch 1 while ε data are stored in latch 2. Latches 1 and 2 store (in binary format) the whole and fractional parts of the complete spacing measurement, computed in units of block length.

By using this simple on-board signal processing, each vehicle computes an unquantized measurement of vehicle separation.[3] Of course, this measurement is sampled data, the sample rate depending on the speed of the preceding vehicle and the guideway block length. In the next section it will be shown that with reasonable block lengths and vehicle speeds the information data rate is high enough to provide smooth vehicle control.

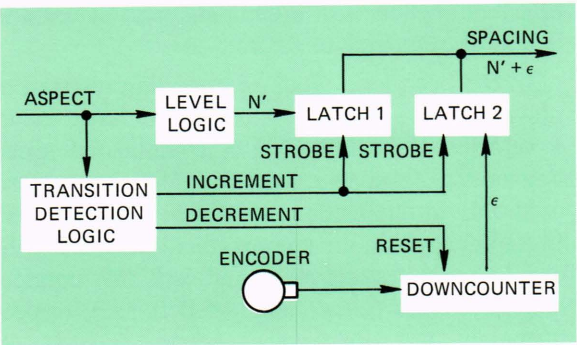

Fig. 5—Spacing measurement instrumentation.

Regulation Control System—A block diagram of a vehicle regulation control system is shown in Fig. 6. The input to this model is either the command line speed (V_L) or the speed of the previous vehicle (V_1), depending on the position of the control mode switch. The output from this model is the speed of the trailing vehicle (V_2).

The vehicle model investigated is a low-order approximation of a propulsion system consisting of a 60-hp, separately excited DC traction motor and motor controller with tachometer feedback. By using complex shaping in the tachometer loop and an integrator in the forward path as compensation, the propulsion system maintains the called-for speed (V_C) with zero steady-state error and little or no sensitivity to changes in wind drag or vehicle loading.[4] A good linear representation of

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[4] S. J. Brown, *Point-Follower Automatic Vehicle Control: A Generic Analysis*, APL/JHU TPR 024/CP 020, Apr. 1973.

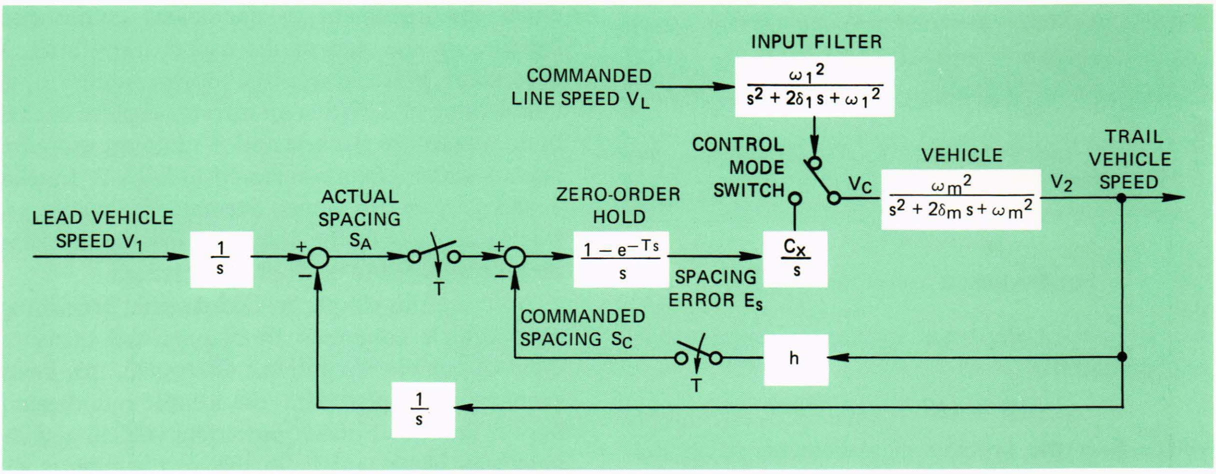

Fig. 6—Block diagram of the spacing control system.

this propulsion system is given by a second-order transfer function with a damping ratio of 0.9 and a natural frequency of 7.5 rad/sec.

In the open-loop mode of operation referred to previously, the vehicle control system functions as a velocity servo following a commanded speed transmitted from the wayside. The input filter, used only in this mode, allows vehicles to respond to step changes in the commanded line speed without exceeding acceleration and jerk rate comfort limits of ±5.0 ft/sec^2 and ±5.0 ft/sec^3, respectively.

When the separation is on the order of one stopping distance, the vehicle operates in the regulation mode. Here the mode switch connects two additional feedback loops around the motor. The outer loop in Fig. 6, which compares actual vehicle positions to obtain vehicle spacing (S_A), is closed through the wayside block system and onboard measurement signal processing. The sampler and zero order hold following S_A in Fig. 6 characterize the sampled data nature of the spacing measurements, the sampler closing each time the lead vehicle crosses a block boundary.

The second control loop resides completely on board the vehicle. Here a commanded spacing (S_C) is formed as a linear function of vehicle speed. The constant gain *h* defines the headway in seconds. Regardless of the actual vehicle speed, this loop automatically adjusts the spacing between vehicles so that the headway remains constant. Note that this feedback loop is also sampled. By synchronizing this sampler with the spacing measurement, a much smoother vehicle response is obtained than if continuous feedback is provided.[3]

Common to both loops is the integrator in the forward path that converts the spacing error (ε_S) into a commanded speed (V_C) and assures zero steady-state spacing error.

The design of the regulation loop centers on choosing C_X since *h* is usually specified from headway constraints. The value for C_X must be chosen to prevent the sampling action from adversely affecting ride comfort and, at the same time, must assure string stability of the platoon, i.e., vehicle speed perturbations must not grow in magnitude as they propagate from vehicle to vehicle through the platoon.

One method of guaranteeing string stability in a platoon is to design the sampled-data control system of each vehicle to have a speed transfer V_2/V_1 which is overdamped.[5] In this study, a single fixed value for C_X provided the needed overdamped response over a 7 to 1 variation in sampling rate. Thus, a simple, constant-gain controller provides a stable platoon operation over a speed range that varies from 11 to 80 ft/sec.

System Performance

All functions of the ABG control system have been exercised in a detailed digital computer simulation.[6] The simulation model included: (a) the

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[5] P. J. Voss, *Stability in a String of Vehicles Employing Vehicle Follower Control,* APL/JHU MCS-6-153, Sept. 1972.

[6] G. L. Pitts, *SOAP—String Operation and Analysis Program—A Simulation of Fixed Block Regulation of Transportation Vehicles,* APL/JHU MCS-3-255, Jan. 1972.

fixed block signaling system, with one merge and one divert junction; (b) a detailed model of the spacing measurement signal processing with the associated downcounters, latches, and cycling logic; (c) the on-board sampled-data controller and control mode switching logic; and (d) a second-order model of the vehicle propulsion system, with hard jerk and acceleration limits installed. Sample simulation runs of an ABG system designed to operate at a constant 6-second headway using 40-foot blocks are illustrated in Figs. 7 to 10.

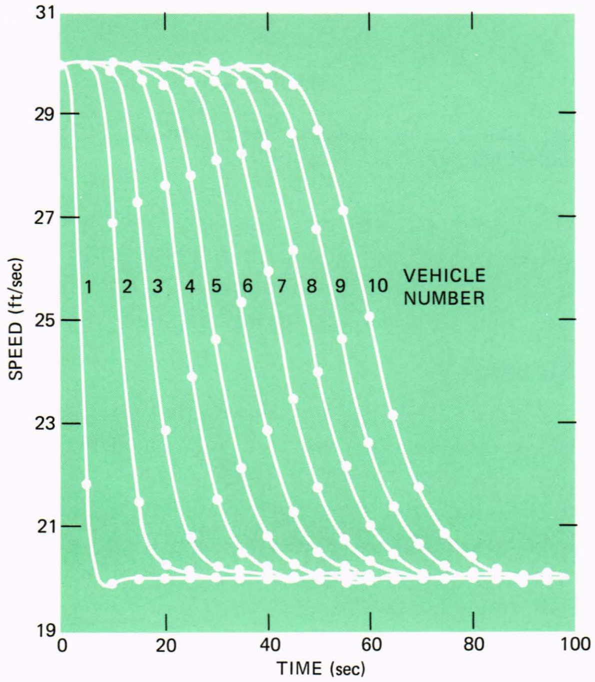

Fig. 7—Sampled-data speed response of a 10-vehicle platoon, block length 40 feet.

Figure 7 shows the response of a 10-vehicle platoon as it crosses from a 30-ft/sec section of guideway into a 20-ft/sec section. The lead vehicle (No. 1) is operating in the open-loop mode, while each of the other vehicles operates in the regulation mode, each following the preceding vehicle. With the 40-foot block used in this example, each vehicle receives a new spacing measurement every 1.33 to 2.0 seconds, depending on the speed of the vehicle ahead. Note the smooth overdamped response of the platoon. This same response has been obtained with updates as infrequent as once every 3 seconds.[3]

Figure 8 shows the corresponding acceleration profiles for each vehicle in the platoon. Deceleration levels are well below the ±5.0 ft/sec^2 comfort limits specified. Note that each vehicle completes the speed transition with lower peak decelerations than its predecessor. This is a property of vehicle-follower regulation systems in general.

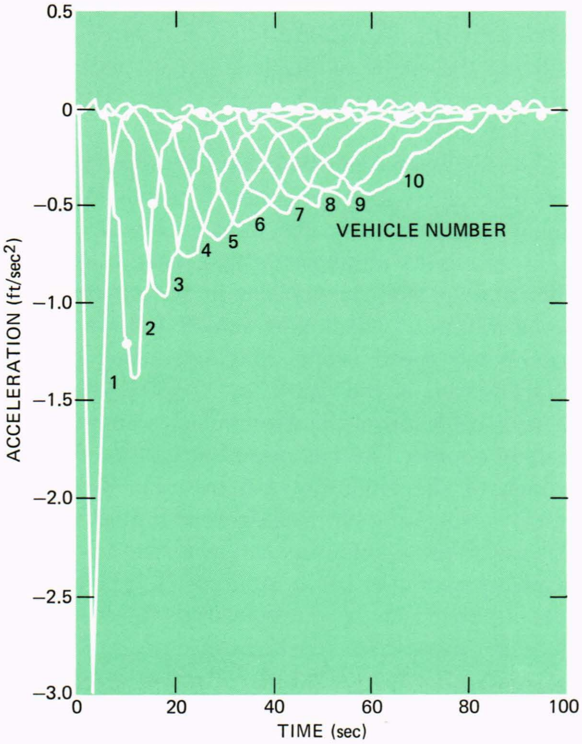

Fig. 8—Sampled-data acceleration response of a 10-vehicle platoon, block length 40 feet.

A frequent criticism of vehicle-follower control philosophies is based on the speed reductions seen in Fig. 7. It is claimed that this speed reduction travels rapidly upstream of the transition point, seriously lowering the effective speed of the transportation system. The speed/position profiles shown in Fig. 9 should allay this fear. Note that each vehicle in the platoon does begin to decelerate farther upstream of the speed transition point than its predecessor, but the effect is not severe. For example, the fifth vehicle in the platoon is only 160 feet from the transition point by the time its speed has been reduced 10% and the twentieth vehicle is only 540 feet from the transition point for the same 10% speed reduction. Of course, the propagation may be stopped at any time by simply breaking the platoon into shorter segments.

One of the important controller functions is to adjust vehicle spacing to maintain constant headway as speed varies. Figure 10 shows the actual separation/speed trajectories for several vehicles in a platoon as they change speed from 30 to 20 ft/sec. All trajectories begin and end on the line of ideal constant headway. The bowing of the trajectories seen at the intermediate speeds is the result of dynamic error in the spacing control. A more sophisticated vehicle-follower control system utilizing the speed of the lead vehicle as well as spacing information can greatly reduce these dynamic errors.

The feedback that exists between adjacent vehicles in a vehicle-follower system provides an operational advantage over the so-called point or cell-follower control strategies in that speed transitions are "anticipated" by vehicles in the platoons. In a cell-follower system each vehicle follows a predetermined speed profile that, over each section of guideway, is the same for all vehicles. Since there is no feedback between vehicles, one vehicle trailing another that has passed into a lower speed section of the guideway will overtake its predecessor.[4] Not until the trailing vehicle itself enters this lower speed guideway can a return to constant headway operation begin. As a result, much larger spacing errors are generated during speed transitions as shown by the dashed trajectory in Fig. 10.

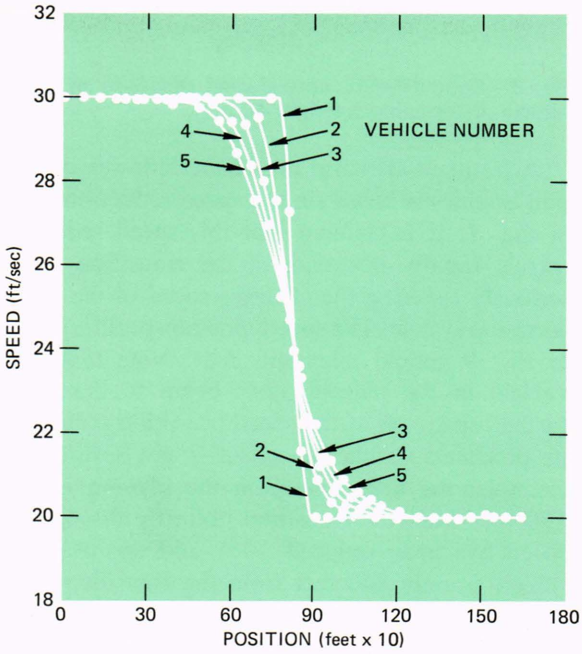

Fig. 9—Speed profile versus position for a 5-vehicle platoon, block length 40 feet.

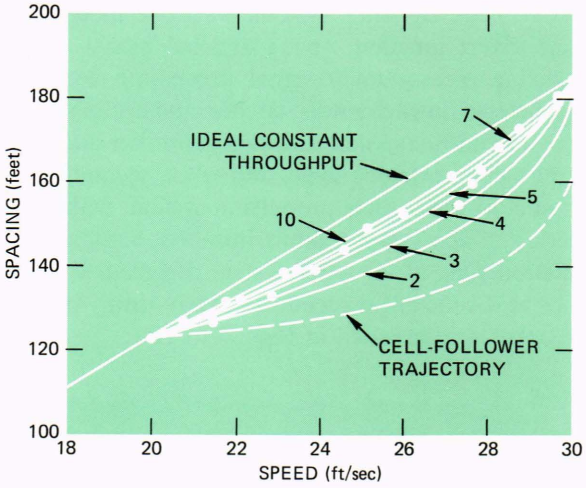

Fig. 10—Dynamic spacing versus speed for a 10-vehicle platoon, block length 40 feet.

The larger spacing error associated with cell-followers necessitates greater initial headways than are required of vehicle-follower strategies. This, in turn, implies a lower guideway capacity.

Summary

This investigation has shown that Augmented Block Guidance provides smooth, accurate, and safe regulation of vehicle spacing. The simplicity of the design and the reliance on existing hardware for key components minimizes the technical risk of this approach, making it attractive for near-term implementation.

Although an overall control concept has been presented, there are four salient contributions that are relevant to applications outside the ABG system context. First, a new approach to fixed block collision-avoidance has been developed that is applicable to short-headway systems, yet uses existing hardware. Analytic design procedures define the largest block length that may safely be used without false alarm braking commands. Second, simple on-board processing can enable a vehicle to convert the block aspect signals it receives into high resolution spacing measurements. Third, the wayside-to-vehicle communication rate can be low and still allow smooth vehicle performance. In this study vehicles were controlled at 6-second headways, with spacing measurements updated as infrequently as once every 3 seconds. Finally, the potential for platoon instability in vehicle-follower strategies can easily be removed with proper control system design.