

[54] **LINEAR MOTOR ACCELERATION
CONTROL SYSTEM**[75] Inventor: **David E. Close**, Denver, Colo.[73] Assignee: **Transportation Technology, Inc.**,
Denver, Colo.[22] Filed: **Jan. 22, 1973**[21] Appl. No.: **325,794****Related U.S. Application Data**[63] Continuation of Ser. No. 150,611, June 7, 1971,
abandoned.[52] U.S. Cl. **318/561, 318/91, 187/29**[51] Int. Cl. **G05b 13/00**[58] Field of Search **318/561, 91; 187/29**[56] **References Cited****UNITED STATES PATENTS**

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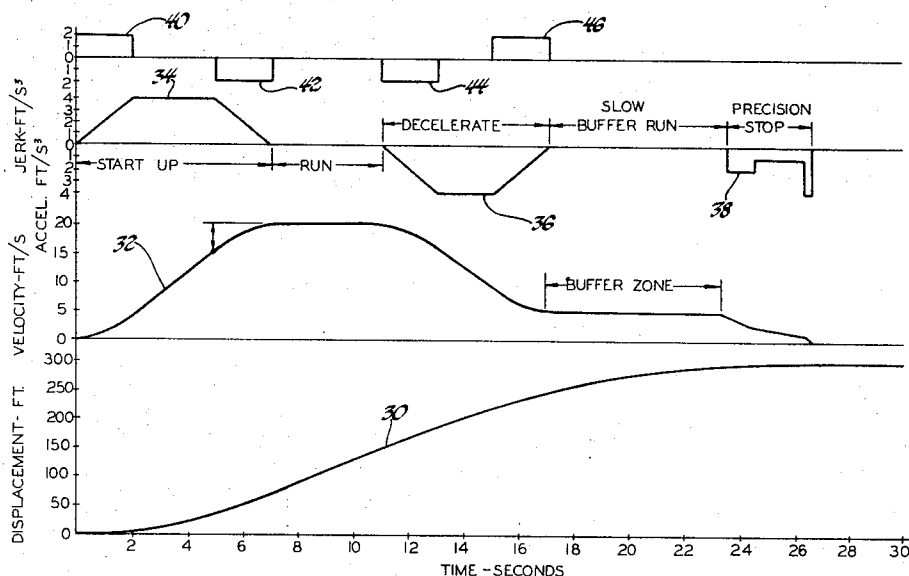
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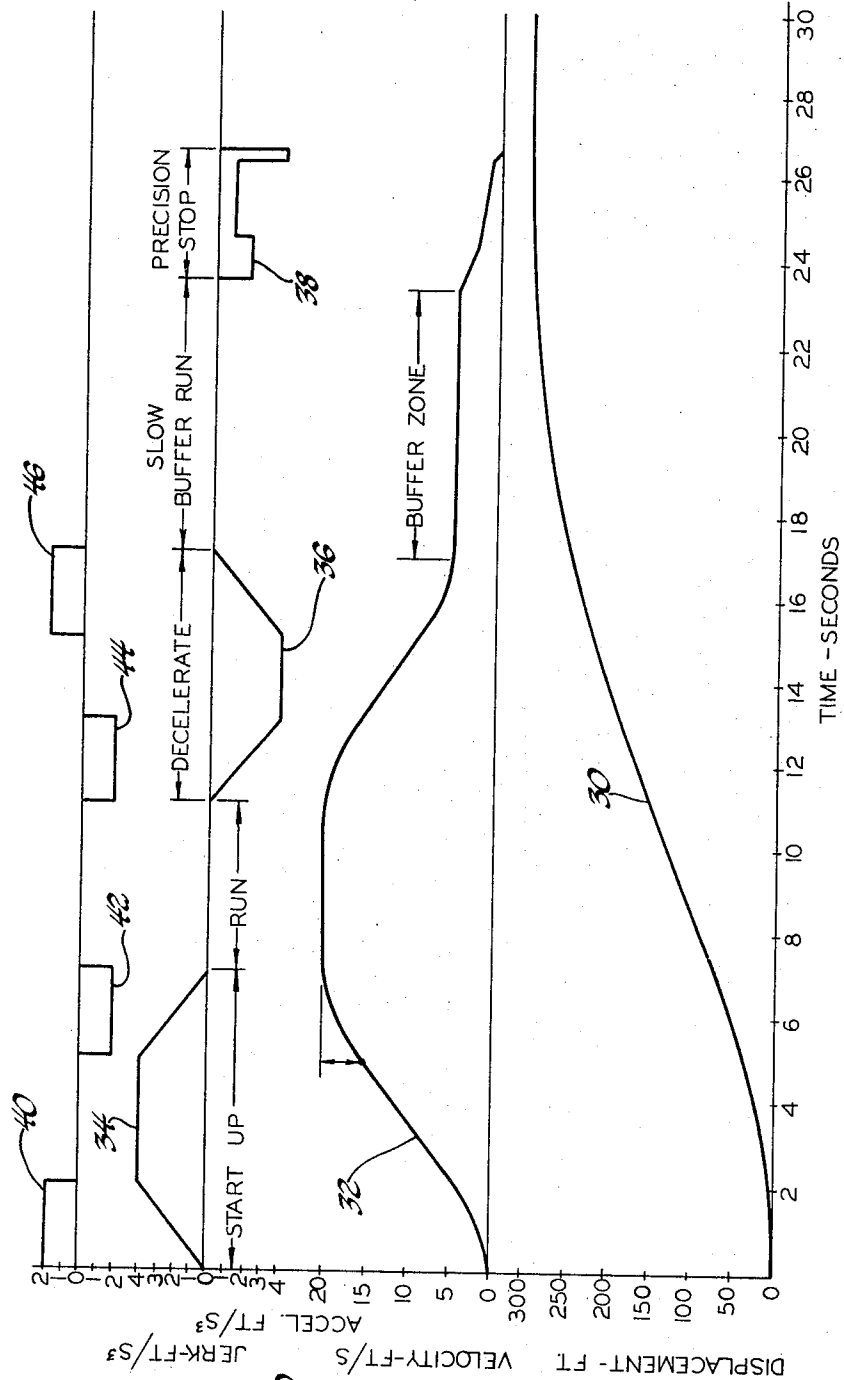
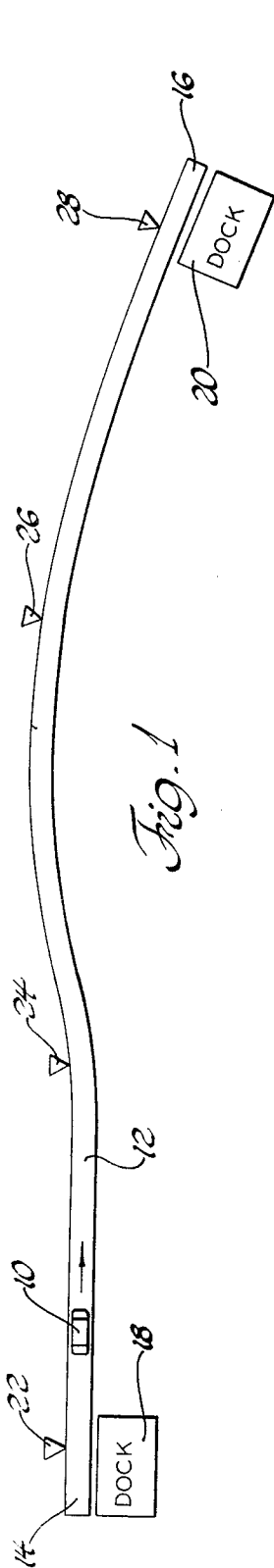
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[57]

ABSTRACT

A control system for programming and executing the displacement characteristics of a transit vehicle propelled by one or more linear motors. Computers are provided for planning speed change points to operate within the program without exceeding maximum acceleration and jerk limits. A precision stop function is carried out in an adaptive manner by control of motor thrust.

6 Claims, 14 Drawing Figures



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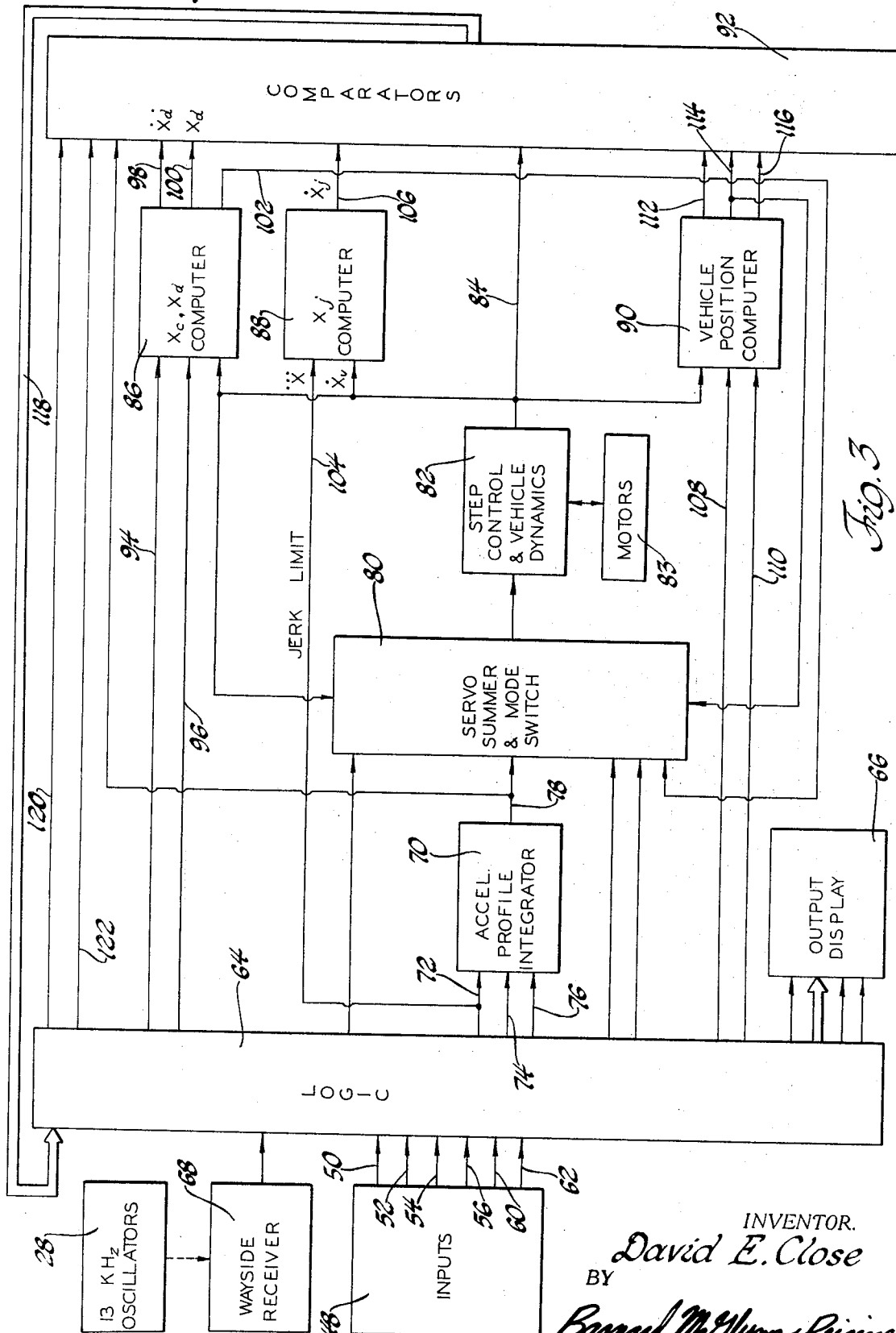
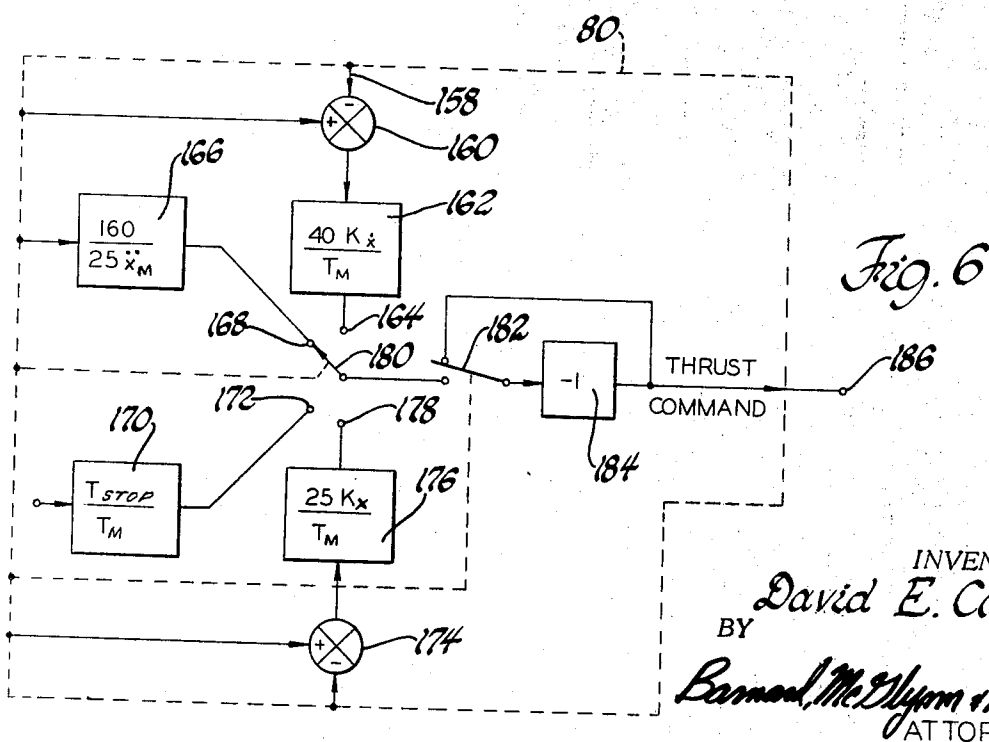
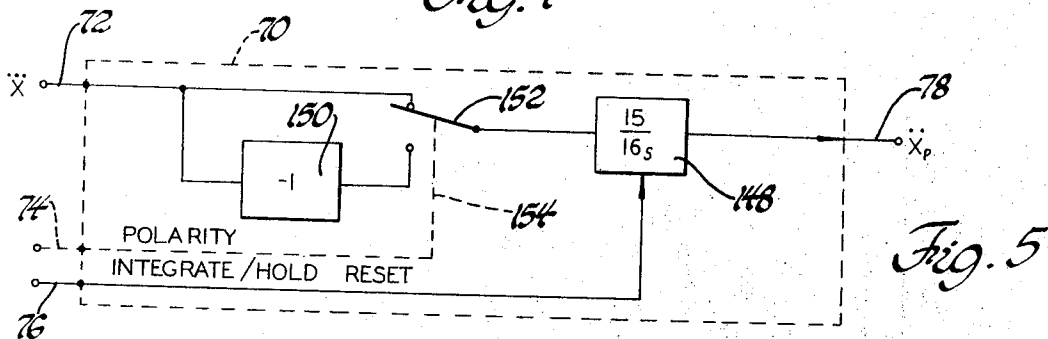
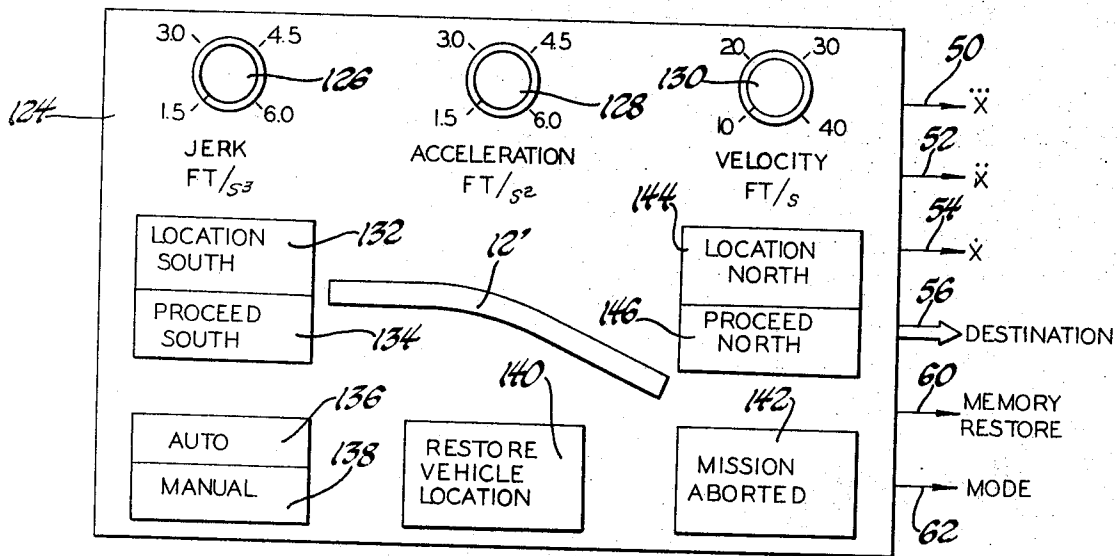


Fig. 3

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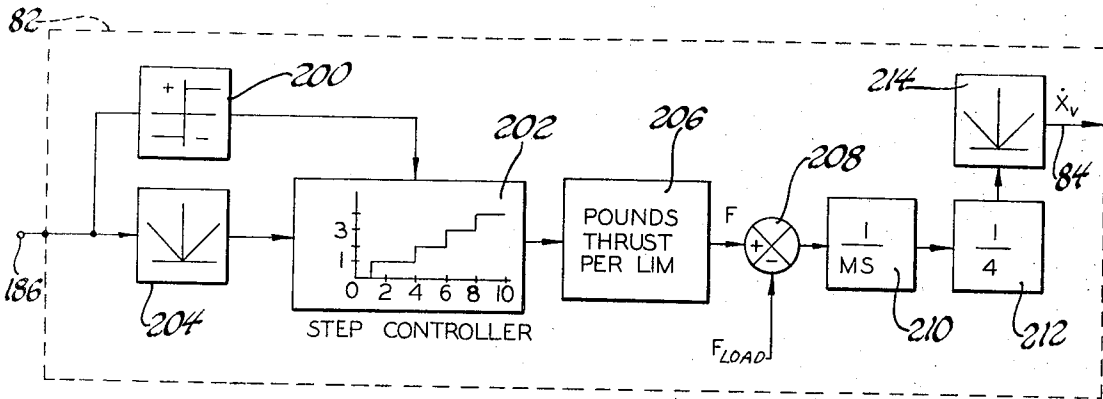


Fig. 7

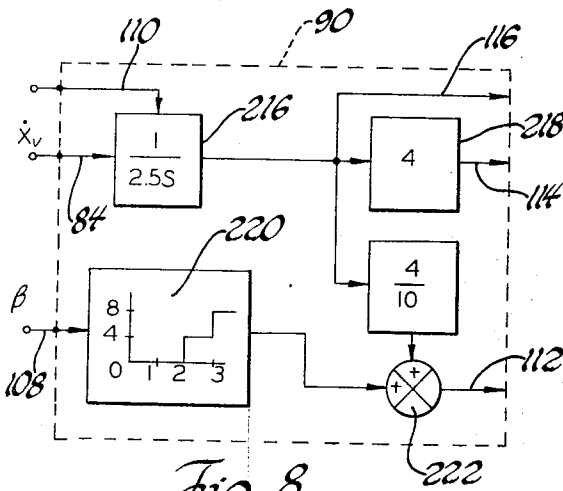


Fig. 8

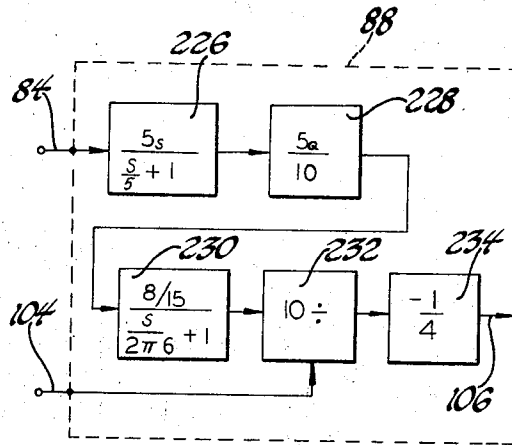


Fig. 9

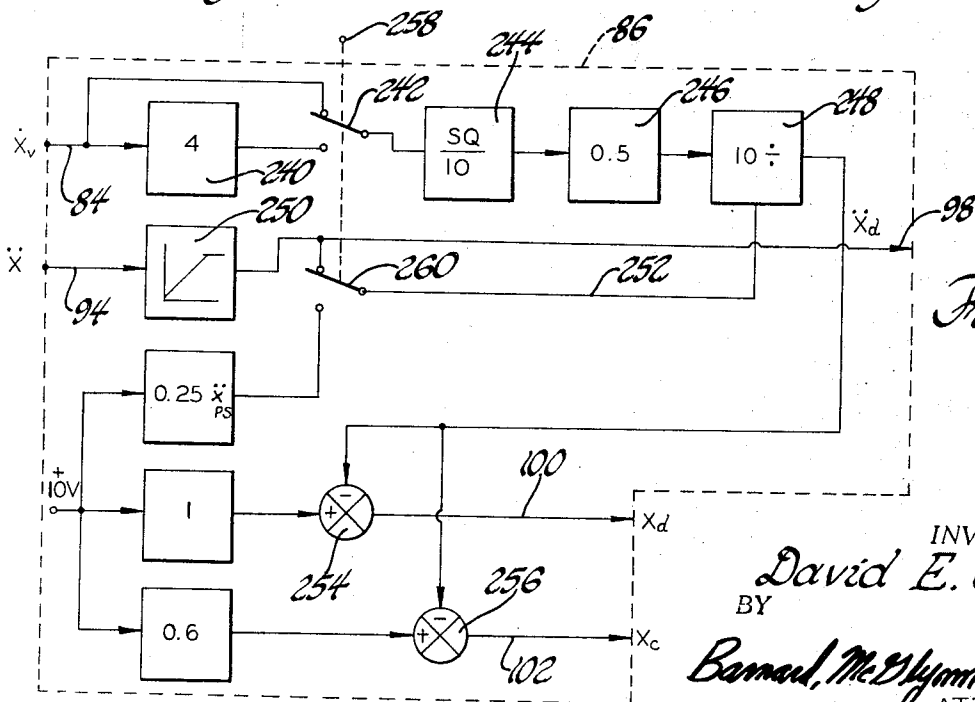


Fig. 10

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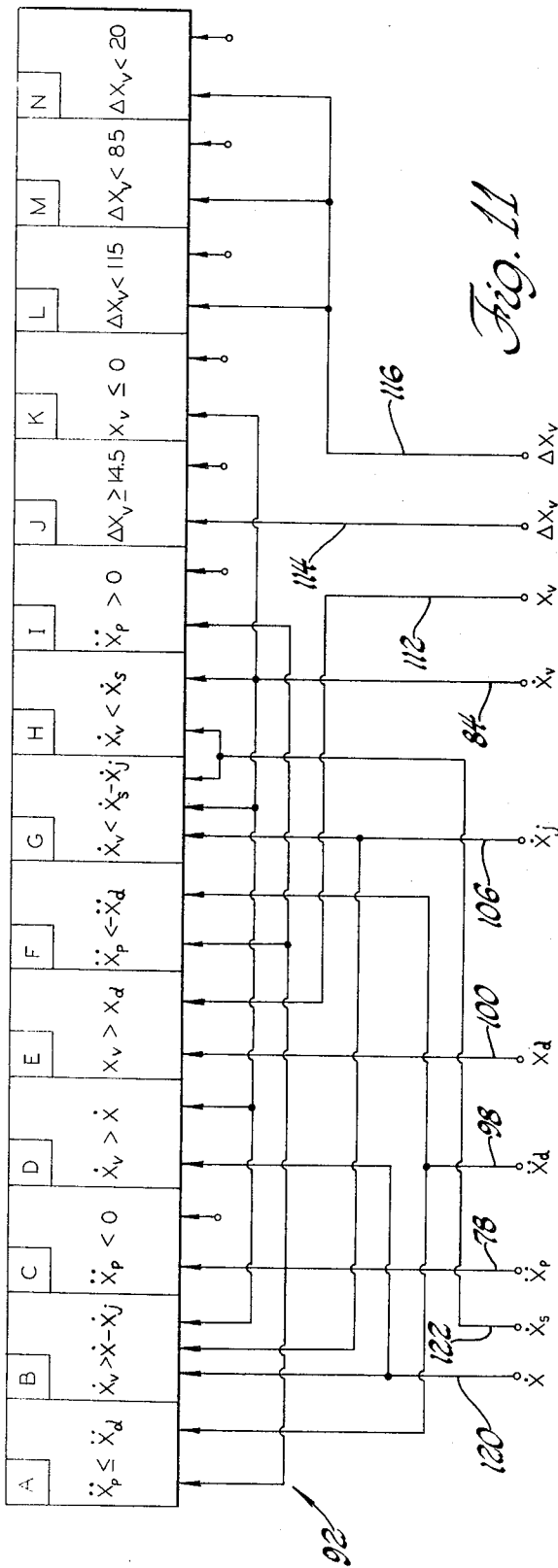


Fig. 11

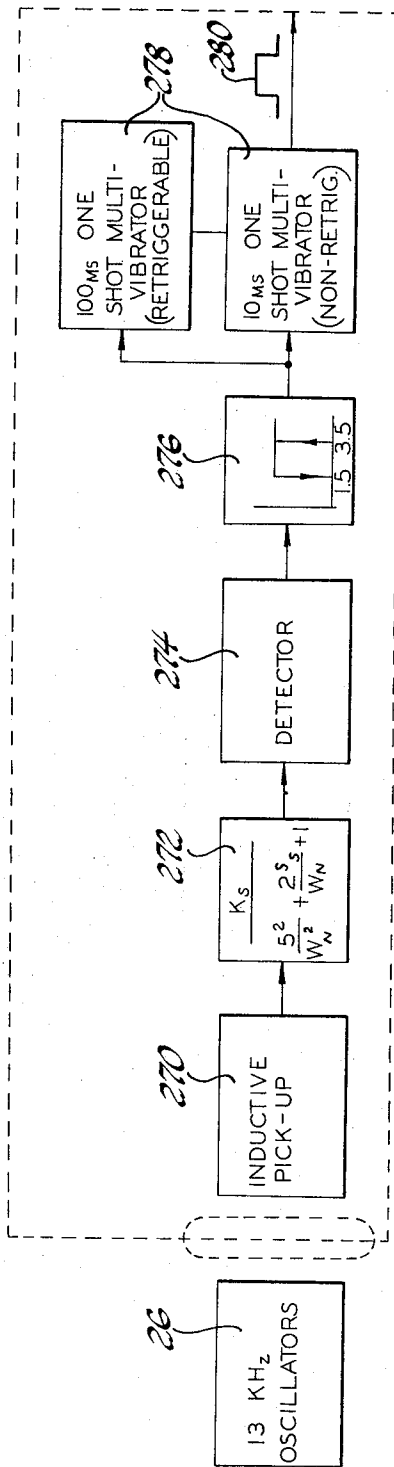


Fig. 12

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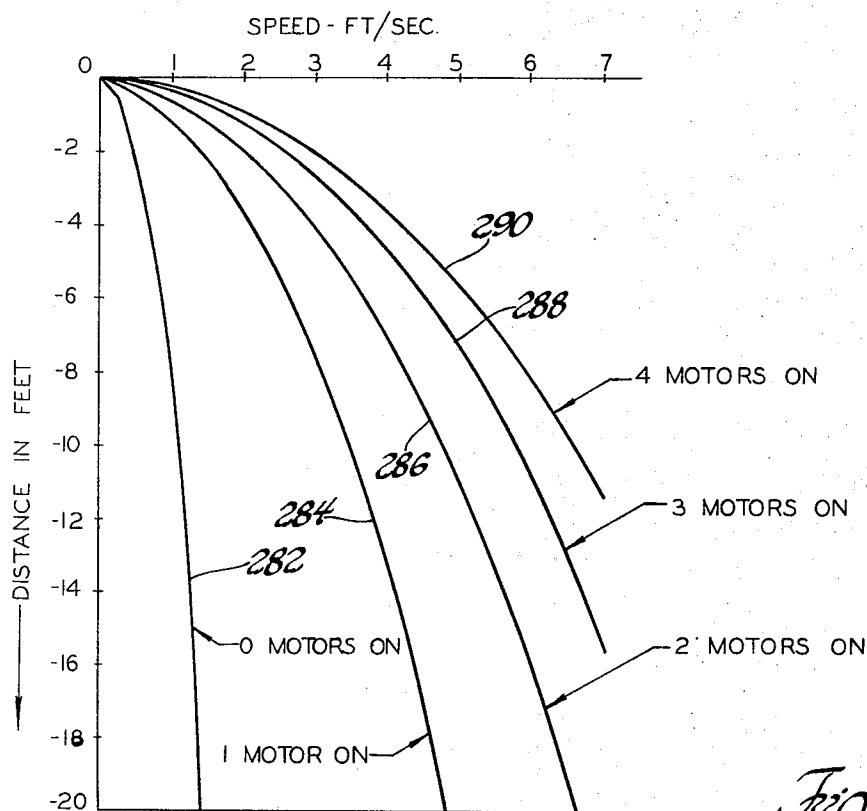


Fig. 13

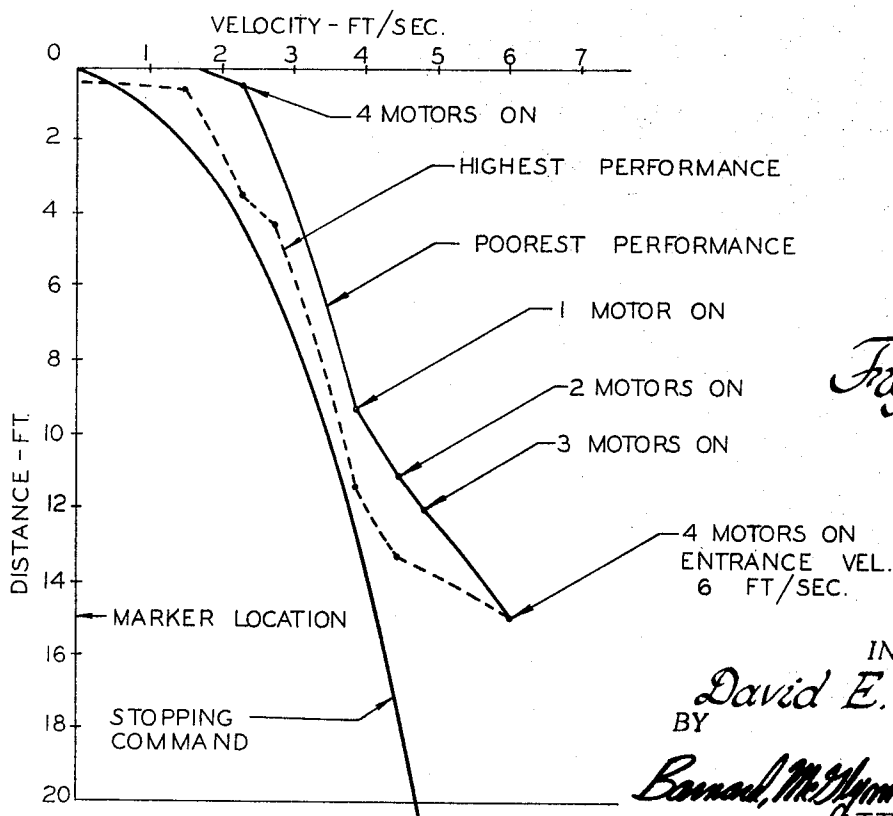


Fig. 14

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LINEAR MOTOR ACCELERATION CONTROL SYSTEM

This is a continuation of application Ser. No. 150,611, filed June 7, 1971, now abandoned.

This invention relates to vehicular speed control systems and particularly to a system for accomplishing the automatic control of vehicle speed changes according to a particular program of speed and speed derivative parameters.

Automatically controlled transit vehicles are well known, particularly in those instances where the vehicle is adapted to follow a fixed roadway. Such fixed roadways may be defined by a multitude of different structures, including rails for wheeled vehicles and guideways for air supported vehicles. The latter type of roadway is not unexpectedly commonly associated with vehicles which are propelled by linear induction motors, one component of such motors being carried by the vehicle and the other component being disposed in a continuous or discontinuous fashion along the roadway.

The most significant functions of an automatic control system for vehicles to which this disclosure is addressed are speed control and stopping. More explicitly, speed control is conventionally concerned with the program of velocity changes, both increasing and decreasing, to follow a program of displacement versus time. Speed control is typically carried out simply by controlling the actual speed at any given time, the manner in which the vehicle is accelerated between speeds being largely, if not totally, a function of the physical capabilities of the motive power means and the speed settings themselves. Stopping and slowing functions are, of course, important if the vehicle is to be brought to a safe and determinable stopping point within the physical limitations of the braking means of the vehicle. To the extent such stopping and slowing functions are controlled by the motive power means, they typically involve little if anything more than making step reductions in power at certain times. A more complex control is required where a reversal of the motive power means is employed to effect the stop or slowing function, for example, where linear induction motors are employed as the motive power means. In these instances a controlled negative acceleration is effected by following a program of modulation in reverse power. A still more complex but more precise stopping function may be accomplished through the use of a servo control mechanism which employs position information to control power level through a feedback loop including a step controller. This system applies such power as is required to follow a precise time-position schedule. Depending upon the gain settings of the overall feedback loop, it is common for such control systems to cycle motors between on and off conditions or to produce a sequence of proportional control steps to achieve the precise stop point. This highly precise function is typically used to control stopping over the last few yards of a run to arrive at a precisely defined docking point.

In accordance with a first aspect of the present invention, vehicle velocity changes both positive and negative are accomplished in a manner which not only effects the desired velocity change, but which schedules the first and second time derivatives of velocity during such changes within predetermined limits. As will be apparent to those skilled in the art, the first time deriva-

tive of velocity is acceleration and the second time derivative of velocity is jerk; that is, the rate at which acceleration is changed in a given interval of time. By maintaining jerk within predetermined limits, the objective ride quality of a transit vehicle may be greatly improved. Thus, the desired jerk limits are ordinarily determined empirically to produce the least undesirable effect among passengers of the vehicle in which the jerk control is employed.

In accordance with a specific embodiment of the invention hereinafter described, a vehicle is propelled by one or more linear induction motors to travel a fixed guideway, thus, substantially eliminating the steering function. Control over velocity as well as the first and second time derivatives of velocity is accomplished such that the velocity changes both increasing and decreasing, are accomplished while maintaining jerk within predetermined limits. A brief study of any typical vehicular speed change will show that an acceleration change occurs both at the beginning and end of very velocity change; for example, a positive jerk quantity is associated with the increasing acceleration at the beginning of a positive speed change and a negative jerk quantity is associated with the decreasing acceleration which occurs at the end of a positive speed change. Accordingly, the objectives of the first feature of the invention are realized in the preferred embodiment for positive accelerations by integrating step commands so as to achieve a maximum desired acceleration without exceeding maximum allowed jerk. During any speed change, a smooth, controlled jerk transition into the commanded speed is accomplished by monitoring the difference between actual velocity and the commanded velocity and, at a precisely determined point in time, introducing a decreasing acceleration which is calculated to achieve the desired smoothing of the speed curve into the steady state condition so as to avoid exceeding the jerk limit. Thus, a vehicle may be programmed either manually or automatically to speed up and/or slow down at various points over a route, each speed change being such as to realize full power capability whenever possible, but without producing undue abruptness. Thus, passenger comfort may be maximized with minimum compromise of efficiency.

In the illustrative embodiment of the invention hereinafter set forth in detail, the vehicle speed change program is accomplished automatically by monitoring displacement of the vehicle along a fixed roadway. The roadway is preferably, but not necessarily equipped with way markers such as small transmitters spaced at prescribed intervals. Thus, the vehicle may periodically update its position information as it travels along the roadway to initiate execution of both positive and negative speed changes as are necessary to traverse the route according to the desired program but without exceeding preselected parameters; these parameters including positive and negative jerk and acceleration limits. As will be made more apparent in the following description, vehicle displacement or progress along the roadway is preferably monitored in terms of the distance remaining to the destination. This permits the calculation of the points at which negative acceleration or slowing functions must be initiated to arrive at the destination without over shooting and without requiring braking efforts which exceed either the physical capabilities of the vehicle or the prescribed jerk and negative acceleration limits.

According to a further feature of the invention, a precision stop function in a plural linear motor driven vehicle is executed without the need for a servo control mechanism of the type which makes repeated reference to external markers and without the need for recycling contact devices for the regulation of current to the motors in a repetitious and inefficient fashion. In general, this is accomplished by providing an external reference which defines the commencement of the precision stop function and which in effect merely updates and checks the accuracy of the distance-remaining information maintained in the vehicle. Thus, the external reference is at least in principle inessential, but is highly desirable for the purpose of extreme accuracy wherein a precise stop position must be accomplished. In accordance with the invention the precision stop function is accomplished by measuring vehicle speed at the time the external reference is passed and by determining from the speed and distance remaining, the number of vehicle motors which must be reverse-energized under predetermined case conditions to stop the vehicle at a constant deceleration rate in the remaining distance to the stop point. This number, expressed in terms of a control voltage, is employed to actuate the desired number of motors in the reverse direction. The speed and distance remaining are constantly monitored to derive a constantly variable control voltage which determines at all times the correct reverse motor energization level to follow a predetermined distance-velocity program. The variable voltage may be employed, as hereinafter described, to operate a step controller, a proportional controller or a hybrid device have both step and proportional control features. Thus, the vehicle is stopped precisely at the desired stopping point without the repetitious cycling of any motor between on and off states. In principle, no motor is switched more than once, thus, minimizing wear and maintenance and again contributing to passenger comfort.

In a preferred embodiment of this last-mentioned feature of the invention, all of the plurality of motors on a plural linear motor driven vehicle may be automatically turned on in the reverse direction when a final and preferably small increment of distance remains to the stop point, thus, to virtually ensure stopping within very close plus and minus tolerance limits of the desired stopping point. In the illustrative example hereinafter described in detail, all four motors of a linear motor driven vehicle are switched on in the reverse direction with approximately six inches remaining to the docking point out of a total precision stop distance of approximately fifteen feet.

Various additional features and advantages of the invention will be best understood from a reading of the following specification which specification sets forth an illustrative embodiment of the invention in such detail as to enable those of ordinary skill in the art to practice the invention. The specification is to be taken with the accompanying drawings of which:

FIG. 1 is a plan view of a roadway to be followed by a linear motor driven vehicle;

FIG. 2 is a four-line chart or graph of vehicular displacement and displacement derivative quantities during a traverse of the run illustrated in FIG. 1;

FIG. 3 is a block diagram of a control system for carrying out the invention;

FIG. 4 is a schematic drawing of a control console used for carrying out the control of the circuit illustrated in FIG. 3;

FIG. 5 is a schematic diagram of a subassembly in the system of FIG. 3;

FIG. 6 is a schematic diagram of another subassembly in the system of FIG. 3;

FIG. 7 is a schematic-block diagram of another subassembly in the system of FIG. 3;

FIG. 8 is another block diagram of another subassembly in the system of FIG. 3;

FIG. 9 is a block diagram of another subassembly in the system of FIG. 3;

FIG. 10 is a block diagram of another subassembly in the system of FIG. 3;

FIG. 11 is a block diagram of another subassembly in the system of FIG. 3;

FIG. 12 is a block diagram of another subassembly in the system of FIG. 3;

FIG. 13 is a family of curves showing the relationship between distance-to-destination and docking points; and,

FIG. 14 is a graph of a typical precision stop execution.

Referring to FIG. 1, there is shown in simplified schematic fashion a vehicle 10 which is adapted to travel a fixed roadway 12 between a departure point 14 and a destination point 16. The length of the roadway 12 between the points 14 and 16 is accurately known. A docking facility is disposed adjacent the departure point 14 so that the vehicle 10 may be moved laterally out of the roadway 12 to permit the through passage of other vehicles; this, of course, assumes that the roadway 12 illustrated in FIG. 1 represents only a portion of an overall roadway system and that the points 14 and 16 do not necessarily represent terminal ends of such a roadway. A similar docking facility is disposed adjacent the destination point 16. The vehicle 10 is preferably of the bidirectional type such that upon reaching the destination point 16 a reversal of identity occurs such that point 14 becomes the destination point.

Vehicle 10 is preferably a multipassenger transit vehicle which is supported relative to a relatively smooth but possibly angled surface of roadway 12 by means of a plurality of low-pressure air bearings and propelled over the roadway by one or more linear induction motors, the specific embodiment employing four motors. Such vehicles are well known in the art and will not be illustrated or described in great detail herein; examples of such vehicles are disclosed in the U.S. Pat. Nos. to Chung, 2,385,228; Falk et al., 3,368,496; and Easton et al., 3,500,765.

Roadway 12 is equipped with a plurality of way markers in the form of uniformly spaced short range transmitters 22, 24, 26, and 28, the typical spacing between such transmitters being 100 feet. The transmitters produce a 13 kilohertz signal which is received by a receiver device on the vehicle 10 to indicate the displacement of the vehicle in 100 foot increments and to update the vehicular displacement record as necessary. Spacings other than 100 feet may be employed and, similarly, nonuniform spacings over the length of the roadway 12 may also be employed.

It will be noted that the transmitter 22 is spaced a fixed distance from the departure point 14 and similarly that the transmitter 28 is spaced by the same distance from the destination point 16. The distances be-

tween the departure and destination points and the respective transmitters 22 and 28 is selected to be on the order of 15 feet and, as well be made more clear hereinafter, these distances define the increment of vehicular displacement over which a precision stop process is carried out at the closing phase of the vehicular run in each direction.

Referring now to FIG. 2, four plots of vehicular displacement and derivations thereof versus time are shown. The curve 20 shown on the lower line of FIG. 2 represents vehicle displacement between the departure point 14 and the destination point 16 over the period of time to traverse the roadway 12 from left to right, as shown in FIG. 1.

The curve 32 illustrates the velocity or first time derivative of the displacement curve 30 experienced by the vehicle 10 during the traverse of roadway 12 between points 14 and 16. It can be seen by reference to curve 32 of FIG. 2 that the velocity increases gradually from a zero value to a steady state increase and then tapers gradually into a constant velocity portion. From the constant velocity interval, velocity again gradually decreases to a relatively low level over a short portion of the roadway 12. Upon reaching the transmitter 28 at approximately 285 feet of displacement, a controlled deceleration interval is entered which interval terminates with a relatively rapid deceleration to a zero velocity condition.

Looking again to FIG. 2, the third line represents a plot of acceleration versus time for the run of the vehicle 10 over the roadway 12 and represents the second time derivative of the displacement curve 30 of FIG. 2. The acceleration plot comprises a first curve 34 which corresponds with the portion of the velocity curve 32 between the zero velocity condition and the maximum velocity condition. The acceleration plot further comprises a second curve 36 which represents the acceleration profile between the maximum velocity condition and the slow buffer zone condition on the curve 32. Finally, the acceleration plot comprises a third portion 38 which represents the acceleration profile during the precision stop phase of the run over roadway 12. The acceleration curve 34 is positive indicating increasing velocity, while acceleration curves 36 and 38 are both negative, indicating decreasing velocity. The precision stop phase represented by acceleration curve 38 again corresponds to the acceleration characteristics of the vehicle 10 over the fifteen feet between the transmitter 28 and the destination point 16. The profile of curve 38 is such as to produce a precise stopping of the vehicle 10 within the longitudinal confines of the docking facility 20.

Referring again to FIG. 2, the fourth and uppermost line indicates a plot of the third time derivative displacement of the vehicle 10 with time, this also being correctly expressible as a second time derivative of the velocity curve 32. The quantity which is represented by the plot on the fourth and uppermost line of FIG. 2 is commonly called "jerk" and represents the rate of change of acceleration. It is this quantity which, along with maximum acceleration, is to be controlled by the vehicular control system hereinafter described.

Analyzing the jerk plot, it can be seen that a first rectangular curve 40 having a predetermined amplitude corresponds with the ramp-like portion of acceleration curve 34 during which time acceleration is increasing linearly. This represents a relatively rapid increase in

velocity. The trailing edge of curve 40 corresponds with the abrupt transition of acceleration curve 34 from the ramp portion to a steady acceleration, this in turn corresponding to the linearly increasing velocity portion of curve 32. A negative jerk curve 42 again having a predetermined negative amplitude equal to the positive amplitude of curve 40 is defined by the ramp-like or linearly decreasing portion of the acceleration curve 34. This in turn corresponds to the smooth transition of the velocity curve 32 between the linearly increasing portion and the maximum velocity value. Accordingly, controllable jerk quantities represented by curves 40 and 42 occur at the beginning and end of a transition between one velocity and another, in this case zero and maximum velocity.

At the termination of the constant velocity, usually high-speed run, a second transition from maximum velocity to the buffer velocity occurs. This transition gives rise to a negative acceleration curve 36, the leading edge or ramp of which corresponds to jerk curve 44, the maximum negative amplitude of which is controllably and selectively set to equal the amplitude of curves 42 and 40 which precede it. The trailing edge of acceleration curve 36 gives rise to a corresponding positive jerk curve 46. Again, curve 46 corresponds in maximum positive amplitude to the absolute amplitude of curves 44, 42, and 40 which precede it. Jerk is ignored in the curve of FIG. 2 during the precision stop phase represented by acceleration curve 38.

In accordance with the invention and with the control system hereinafter described, the maximum amplitudes of the acceleration curves 34 and 36 as well as the jerk curves 42, 44, and 46 are controlled automatically in accordance with predetermined settings, these settings normally being imperically determined to be within the physical capabilities of the propulsion system and at the same time within the tolerance levels which are prescribed by human reaction.

FIG. 3 illustrates in block diagram form the overall design of the control system for executing the control functions necessary to produce the physical displacement characteristics illustrated in FIG. 2. It is to be understood that the only fundamentals in the curves of FIG. 2 insofar as this invention is concerned involve the concept of limitations on positive and negative acceleration and jerk and the precision stop phase. Therefore, although FIG. 2 is presented with specific values and with specific sequences of speed changes, it is to be understood that these specifics are variable as between systems and individual vehicle runs.

Referring specifically to FIG. 3, the system comprises a computer type logic network including an input unit 48 having an output line 50 specifying the preselected jerk limit, that is, the maximum amplitude of curves 40, 42, 44, and 46 in FIG. 2. Input unit 48 also includes an output line 52 which carries an electrical signal specifying the selected line acceleration limit, that is the maximum amplitude of positive and negative acceleration curves 34 and 36. Unit 48 further comprises an output line 54 which carries an electrical signal specifying maximum line speed, that is, the maximum amplitude of curve 32 in FIG. 2. Input unit 48 may further include output line 56, 60, and 62 for specifying additional miscellaneous information for the benefit of a computer controlled system. In the example shown, this information may include the destination identity, the memory restoration signal, and the operating mode either man-

ual or automatic. All of the signals presented by the input unit 48 are in the form of electrical signals, that is, voltages and may be weighted with different weighting functions according to the various gain and other electrical component factors which are involved in the system. Therefore, it is to be understood that the actual weighting factors illustrated in FIG. 3 are illustrative only.

All of the output lines 50, 52, 54, 56, 60, and 62 are connected to a logic unit 64 which preferably takes the form of integrated circuit computer logic elements to suitably energize the various output lines therefrom in accordance with the nature of the inputs from unit 48 as well as the other units which are connected in input relation to the logic unit 64. Five output lines from logic unit 64 are connected to an output display unit 66 which is preferably disposed in the vehicle 10 for displaying the state of the vehicle to an operator or attendant at all times. These outputs include an indication of the mission abort function, the location of the vehicle, the operating mode, and the restoration of the memory of any control computer employed.

Another device occupying an input relationship to the logic unit 64 is the wayside receiver 68 carried by the vehicle in response to the 13 kilohertz signals from the wayside transmitters 22, 24, 26, and 28 in the system of FIG. 1. The transmitter 28 is illustrated in a coupled relationship with the receiver 68 for purposes of illustration. The output of the receiver 68 is connected to the logic unit 64 to indicate travel increments of 100 feet as well as to indicate passage of the precision stop external reference marker transmitters 22 and 28.

The system of FIG. 3 includes a current integrator 70 known as the acceleration profile integrator whose function is to selectively integrate a dc voltage so as to follow the shape of the desired acceleration curve, for example 34 and 36, during acceleration and deceleration phases of any given run. The jerk limit signal appears on line 72 and is connected in input relationship to the integrator 70 to control the slope or rate of integration of the acceleration and deceleration curves 34 and 36 respectively. By controlling the slope of the acceleration curves the amplitude of the jerk curves 40 and 42, for example, are automatically regulated since jerk amplitude is a direct function of the slope of the acceleration curve. The polarity or direction of integration, either positive or negative, is determined by a polarity signal which appears on line 74 from the logic unit 68. This, of course, is determined by the scheduling for any given run including such specific factors as position and speed.

The output of the acceleration profile integrator 70 appears on line 78 and is connected first to a servo summer and mode switch unit 80 and secondly to an input of a comparator unit 92 to be described. The overall function of the servo summer and mode switch 80 is to compare commanded system quantities to actual system quantities, thus, to generate error signals for control purposes. The output of the summer and mode switch unit 80 is connected directly to a control unit 82 which in this specific application includes an on-off control unit for each of the four linear induction motors used to propel the vehicle. Thus, the waveform which is generated by the acceleration profile integrator 70 is applied through the summer and mode switch unit 80 and the step controller unit 82 to the motors 83 of the vehicle 10. The step control and vehicle dynam-

ics unit 82 includes means, such as a tachometer generator, for producing a signal proportional to vehicle speed or instantaneous velocity. This signal appears on output line 84 and is applied simultaneously to the summer and mode switch unit 80, the first special purpose computer 86, to a second special purpose computer 88, to a third special purpose computer 90, and to the comparator unit 92. The vehicle velocity transducer may employ a rolling contact device which engages the roadway 12 to drive a tachometer generator or it may be of an optical type responsive to certain indicia distributed along the roadway, the particular design of this transducer being incidental to the present invention. However, the presence of the transducer is of extreme importance to the operation of the system of FIG. 3 as the vehicle velocity signal is that from which the other fundamental displacement quantities illustrated in the curves of FIG. 2 are derived. In other words, velocity may be integrated to indicate position or total displacement and it may be differentiated to indicate actual acceleration and jerk.

The special purpose computers 86, 88, and 90 are all analog devices in the implementation of the system of FIG. 3 and are employed to compute quantities which are used in the jerk control and position and speed control functions in the system. The details of the special-purpose analog computers 86, 88, and 90 are illustrated in FIGS. 10, 9, and 8, respectively. By way of general explanation, the computer 86 is a bi-model computer which produces outputs on lines 98, 100, and 012 proportional to the limited acceleration and deceleration level, the position for initiation of deceleration from line speed, and the position command for a computed precision stop, respectively. The first two signals on lines 98 and 100 are connected to the comparator unit 92 and the third signal on line 102 is connected to the input of the servo summer and mode switch 80. The special-purpose analog computer 88 produces an output on line 106 proportional to advance speed increment necessary to provide the speed tapering jerk control junction representative of point 224 of FIG. 2. This signal is connected to the comparator unit 92. Special-purpose analog computer 90 produces outputs on lines 112 and 114 proportional to vehicle position and the vehicle position between any two wayside signal transmitters, respectively. These signals are connected to the comparator unit 92. A third output from vehicle position computer 90 appears on line 116 and is also proportional to the vehicle position between wayside signal transmitters but is weighted by a different factor for a second comparison in the unit 92. The signal on line 114 is also connected back to the servo summer and mode selection switch 80.

Additional signals which are connected from the logic unit 64 to the computer 86 are the signals on lines 94 and 96 which are proportional to the selected maximum acceleration and deceleration level and the computing mode, either X_c or X_d , respectively. Signals from the logic unit 64 to computer 90 appear on lines 108 and 110 and correspond to the current number of wayside signal transmitters passed and the reset signal for the integrator which forms part of the computer 90 as illustrated more completely in FIG. 8. Finally, lines 120 and 122 from the logic unit 64 to the comparator unit 92 carry signals which are proportional to selected line velocity and station area velocity respectively. The outputs of the comparator unit 92 are connected by way

of a bus 118 to the input of the logic unit 64 as shown.

Referring now to FIG. 4, there is shown a console 124 which contains the input unit 48 and the output display unit 66 from the system of FIG. 3. Console 124 contains potentiometers which are regulated by control knobs 126, 128, and 130 to establish the settings for jerk limit, acceleration limit, and maximum line velocity, respectively. In the exemplary illustration of FIG. 4, the jerk in feet per second cubed may be set at a limit between 1.5 and 6.0. Similarly, acceleration in feet per second squared may be set at any limit between 1.5 and 6.0. Line velocity may be set at any speed in feet per second between 10 and 40. The jerk limit signal appears on line 50, the acceleration limit signal appears on line 52, and the velocity limit signal appears on line 54 in correspondence with the numbering on unit 48 in FIG. 3.

The output display portion of the console 124 contains stop and 134 for indicating the movement of the vehicle 10 toward the destination point 16 arbitrarily designated as the south location. Console 124 further includes lights 136, 138, 140, and 142 which indicate the function suggested by the legends in the drawing. Lamps 144 and 146 are illuminated when the vehicle is proceeding back toward the point 14 on the roadway 12 of FIG. 1. Finally, a small facsimile of the roadway 12' may be placed on the face of the console 124 to illustrate the approximate progress of the vehicle along the roadway by means of a moving light beam. All of the instrumentation and electrical apparatus indicated in the console 124 of FIG. 4 is well known and, thus, discussions of lighting, circuitry, and so forth are not deemed to be necessary to enable one of ordinary skill in the art to practice the invention.

Referring now to FIG. 5 the internal arrangement for the acceleration profile integrator 70 is shown in greater detail to comprise an integrator 148 of conventional electronic design connected to receive the jerk limit control signal on line 72 which is established by the setting of the control knob 126 on the jerk limit potentiometer in the console 124 of FIG. 4. The jerk limit signal is switched to bypass or pass through an inverter 150 for polarity reversal in accordance with the position of a switch 152. The switch 152 is schematically controlled by a solenoid link indicated by broken line 154 which in turn is controlled by the polarity signal on input line 74. The integrate-hold-reset signal appears on line 76 to control the instantaneous function performed by the integrator 148. The output of the integrator which is the acceleration waveform to be applied through appropriate gains to the linear motors appears on line 78. Voltage sources and other detailed elements of electronics are omitted from the schematic diagram of FIG. 5 for the sake of simplicity since such details will be apparent to those of ordinary skill in the art.

Looking now to FIG. 6, the internal details of the servo summer and mode switch unit 80 from the system of FIG. 3 are shown in greater detail. As previously mentioned, the function of unit 80 is provided summing and mode selection functions, this being carried out by a suitable selection of differential adders, variable gain amplifiers, and switches. More particularly, the command velocity signal on line 156 from the logic unit 64 is connected to one input of a differential adder 160 while the actual vehicle velocity signal on line 158 from the velocity transducer in unit 82 of FIG. 3 is con-

nected to the other input. The difference signal, that is, the difference in instantaneous value between commanded and actual vehicle velocity, is applied to an amplifier 162 the gain of which is selected to minimize the speed error of the vehicle. The output of amplifier 162 appears at terminal 164. The output of the integrator 70 appearing on line 78 is applied through an amplifier 166 to a second terminal 168. A third amplifier 170 having a negative input supply voltage has the output connected to a terminal 172 for a maximum stop thrust command. The vehicle position between wayside signals appearing on line 114 and the position command for a precision stop signal on line 102 are connected to differential inputs of differential adder 174 the output of which is connected through amplifier 176 to the terminal 178. A loop mode control switch 180 operating under the control of loop mode signals appearing on line 194 from the logic unit 64 in FIG. 3, these loop mode control signals being schematically connected by means of a stepper switch to the wiper arm 180 of the switch arrangement for mode control. It will be understood that a solid state stepper switch is generally preferable to a mechanical switch. Accordingly, the unit 80 may place the control system in a position loop, a velocity loop, an acceleration-deceleration loop, and a final stop loop represented by the terminals 178, 164, 168, and 172, respectively. The terminal 180 of the loop control switch is connected through a polarity control switch 182 for directing the signal through or around an inverter 184 to the thrust command output terminal 186. This terminal is in turn connected to the step control block 82 for direct control over the vehicle linear motors. The position of switch 182 is determined by the signal appearing on line 190 which in turn determines the appropriate position of switch 182.

Looking now to FIG. 7, the overall design of the step control unit 82 is shown to comprise an input line 186 which is connected a bipolar bang-bang amplifier 200 for polarity control over a conventional five-level step controller 202. The signal on input line 186 is also connected through an absolute value amplifier 204 for application to the step controller 202 for direct control over the number of linear motors to be selected for actuation at any time. The polarity signal, of course, determines the direction of thrust to be produced by the actuator linear motors.

Step controller 202 may be of conventional design and in the simplest case is adapted to assume any one of five output conditions, thus, to actuate or energize any combination of four linear induction motors for the propulsion and braking of the vehicle 10 in response to the input voltage level from amplifier 204. The output block 206 represents the number of pounds of thrust per linear induction motor and, in the system dynamics motif followed by FIG. 7 is combined differentially in a hypothetical differential adder 208 with the load represented by the vehicle itself, wind effects, friction, if any, and other factors, if any, to effect speed acceleration and jerk quantities of the vehicle. The vehicle itself as well as the speed transducer which is carried by the vehicle is represented by block 210, the output signal of the speed transducer being indicated by suitable legend in FIG. 7. A proportional voltage divider 212 for scaling purposes and an amplifier 214 are provided in series with the speed transducer to provide the actual vehicle velocity signal on line 84 which is connected to

the various elements in FIG. 3, as previously described.

Referring now to FIG. 8, the vehicle position computer 90 from the system diagram of FIG. 3 is shown in greater detail to comprise an input line 84 for the actual velocity signal, this line being connected to an integrator 216 which is instructed to integrate or be reset by the signal appearing on line 110 from the logic unit 64. The integrator 216 is reset each time a wayside transmitter is passed and, thus, the output of the integrator 216 represents the vehicle position between wayside signals and, thus, is a scalar quantity representing something between zero and 100 feet. This signal is applied to a first amplifier 218 which provides a first weighted signal proportional to the vehicle position signal on output line 114, this line being connected both to a comparator and comparator unit 92 and to the servo summer and mode switch unit 80 of FIG. 6, as previously, described. In addition, the vehicle position signal appears on output line 116 which is connected directly to a comparator in unit 92. A way-side update signal is provided by the wayside update function generator 220 which receives the input on line 108 from the logic unit 64 proportional to the number of wayside signals received. The transfer function of unit 220 is a staircase waveform which is applied to one input of a full adder 222. The other input is received from the output of amplifier 216. The difference signal which is proportional to vehicle position appears on output line 112 and, thus, represents the total vehicle displacement, that is, the sum of the number of wayside transmitters passed plus the distance travelled since passing the last wayside transmitter. The overall purpose of the computer 90 is to determine, to various scale factors and reference points, the distance traveled by the vehicle by integration of vehicle velocity.

Looking now to FIG. 9, the details of the special purpose analog computer 88 are illustrated in detail. The function of analog computer 88 is to determine the velocity increment or difference between actual velocity and commanded velocity during a speed change at which the initiation of jerk control should be started. The function of computer 88 is represented by the equation:

$$\ddot{X}_j = \ddot{X}_v^2/2\ddot{X}$$

where $\ddot{X}_v$ equals the the actual vehicle acceleration, where $\ddot{X}$ equals the desired jerk limit. To give a more graphic explanation, reference should be taken to curve 32 of FIG. 2 where a point 224 represents the interface between the linear portion of curve 32 and the sloping portion which tapers into the constant velocity run. The velocity difference in feet per second between the instantaneous velocity at point 224 and the maximum velocity on curve 32 represents the quantity which is computed by the computer 88.

Looking again to FIG. 9, computer 88 comprises an input line 84 which receives the actual velocity signal from the tachometer generator or speed transducer in unit 82. This signal is applied to a differentiator 226 and to an electronic squaring module 228 to derive a quantity proportional to actual vehicle acceleration squared. This signal is applied to an amplifier 230 which controls scale gain and which also filters noise. The output of amplifier 230 is connected to an electronic divider 232 the output of which is controlled by the jerk level potentiometer setting which represents

the dividend and appears as a voltage on control line 104. The output of divider 323 is connected through a second amplifier 234 for inversion and scale control purposes to the output terminal 106. By comparator and control circuitry hereinafter described, the signal appearing on line 106 controls the initiation of jerk control to reduce the acceleration of the vehicle over the necessary time period during a speed change from a first to a second velocity.

Looking now to FIG. 10, the details of the special-purpose computer 86 are shown. Computer 86 is a bi-modal device which computes two independent but similar equations:

$$x_d = 250 - \dot{X}_v^2/2\ddot{X}_d \text{ and} \\ X_c = 15 - \dot{X}_v^2/2\ddot{X}_{ps}$$

Where:

X_d = position at which controlled deceleration should commence

250 = specific system constant

$\dot{X}_v$ = vehicle velocity

$\ddot{X}_d$ = desired deceleration limit

X_c = commanded position for precision stop

15 = specific system constant

$\ddot{X}_{ps}$ = desired level of constant deceleration during precision stop.

Thus, computer 86 provides three output signals, the first representing the limited acceleration and deceleration level and appearing on line 98, the second being a signal indicating the position of the vehicle for initiation of deceleration from line speed and appearing on line 100 and the third being a signal indicating the command vehicle position for the precision stop phase, this signal appearing on line 102.

Considering the first two signals, the actual vehicle velocity signal on line 84 is connected either through or around a gain module 240 depending upon the position of mode control switch 242 to an electronic squaring amplifier 244, a scaling gain 246, and an electronic dividing module 248, the dividend for which is proportional to selected maximum acceleration and deceleration level. This quantity being represented by control signals on line 94. The control signal on line 94 is applied to the limiting amplifier 250 having a transfer characteristic, as shown, and thence, over line 252 to the control terminal of divider 248. The output of amplifier 250 is connected directly to output line 98 which goes to comparator 92 for purposes of limiting the output of the acceleration profile integrator 148 discussed previously.

The output of amplifier 248 is connected to inputs of differential adders 254 and 256 which affect signals on output lines 100 and 102, respectively. Other input to differential adder 254 is simply a 10 volt signal representing a predetermined distance at which a selected speed is to be reached so that the resulting output on line 100 is proportional to the position for initiation of deceleration from line speed, this position corresponding to the leading edge of the jerk curve 44 in the graphic illustration of FIG. 2. The other input to adder 256 is a six-volt signal such that again the output on line 102 is a position signal indicating a command for a precision stop, this corresponding to the leading edge of curve 38 in FIG. 2. The control logic 64 initiates control connection 258 to select the mode switches 242 and 260 to switch the computer of FIG. 10 from the deceleration position computation position or mode

shown to the precision stop calculation position or mode which represents the next function to be performed by the computer 86 of FIG. 10.

Looking now to FIG. 11, the comparator unit 92 is shown to comprise fourteen comparator circuits A through N connected to receive various combinations of the control signal quantities on lines 120, 122, 78, 98, 100, 106, 84, 112, 114, and 116. It will, thus, be appreciated that many of the control functions which are performed by the system of FIG. 3 lend themselves to straightforward comparisons between signal quantities, thus, to determine times, positions, and other quantity values at which control functions are to be initiated.

Comparator A receives the signals on lines 98 and 78 and produces an output whenever the signal quantity representing command acceleration is equal to or less than the signal quantity representing the limit on acceleration and deceleration. Comparator B is connected to receive the signal quantities on lines 120, 106, and 84 and functions to produce an output when the signal quantity representing actual vehicle velocity is greater than the difference between the maximum selected line velocity and the computed velocity increment for initiation of jerk control. Comparator C is connected to compare the signal quantity on line 78 representing command acceleration with a zero voltage quantity and produces an output whenever the former is less than zero. Comparator D receives the signal quantities on lines 120 and 84 and produces an output when actual vehicle velocity is greater than the selected maximum line velocity. Comparator E is connected to compare the signal quantities on lines 100 and 112 and produces an output whenever the actual vehicle position is greater than the position for initiation of deceleration from maximum line speed, that is, comparator E determines when the vehicle should be decelerated for an approach to a station. Comparator F receives the signal quantities on lines 78 and 98 and produces an output whenever the command acceleration is less than the inverse of the maximum acceleration and deceleration limit. Comparator G is connected to receive the signals on lines 106, 84, and 122 and produces an output whenever actual vehicle velocity is less than the difference between the selected station area velocity and the computed velocity increment for the initiation of jerk control. Comparator H receives the signals on lines 122 and 84 and produces an output whenever the actual vehicle velocity is less than the station velocity. Comparator I produces an output whenever the command acceleration appearing on line 78 is greater than zero. Comparator J connected to receive the signal on line 114 and to produce an output when the vehicle position between wayside signals is equal to or greater than 14.5 feet, this number representing the distance following the passage of precision stop wayside oscillator 28 at which time all four linear induction motors to the vehicle 10 are to be turned on for the final stop phase. Comparator K is connected to compare the signal on line 84 representing actual vehicle velocity with zero and produces an output whenever the actual vehicle velocity is equal to less than zero. This, of course, indicates the crossover from movement in one direction to the other. Comparator L compares the vehicle position between wayside signals with a constant, in this case 115 feet, to determine whether vehicle position information is accurate. To do this the signal is generated by comparator L as long as the vehicle displacement be-

tween wayside signals is less than 115. If the signal exceeds 115, the output from comparator L is switched, thus, causing an abort function to take place. Comparator M is the converse of comparator L in that it compares vehicle position between wayside signals and produces an output as long as the vehicle position between wayside transmitters is less than 85. The combination of comparators L and M permits the system to determine whether a vehicle position error of 15 feet or more is seen during any 100 foot travel increment. If the error exceeds 15 feet, either plus or minus, the mission may be aborted. Finally, comparator N is connected to compare the actual vehicle position between the wayside signals to twenty and to produce an output as long as the signal is less than 20 which is also used to abort the control under starting conditions.

The circuit of FIG. 11 does not indicate the actual connections between the output of the comparators A through N and the logic unit 64 of FIG. 3, but the illustrated relationship between the outputs of the comparators and the output of the logic unit 64 is believed to be sufficient disclosure to those of ordinary skill in the art to fully indicate the require nature of the logic equations in the unit 64.

Looking now to FIG. 12, the details of a wayside receiver 68 are disclosed. Receiver 68 comprises an inductive pickup 270 which may be inductively linked to one of the oscillators, such as oscillator 26, which are placed along the roadway 12. The output of the inductive pickup 270 is connected through a bandpass filter 272 to a detector circuit 274, the output of this unit being connected to a Schmidt trigger 276. The output of Schmidt trigger circuit 276 is connected through pulse shaping logic 278 to form sharp 10 millisecond pulses 280 which are directed to the logic unit 64 in the system diagram of FIG. 3.

Looking now to FIG. 13, there is shown a graph representing a family of curves indicating the relationship between the distance from a docking point and a vehicle speed which must be realized at those distances to precisely bring the vehicle to a stop at the dock point using a given number of motors and, thus, representing a constant level of deceleration. In FIG. 13, the first curve indicates the natural deceleration of the vehicle 10 with no motors on and producing reverse thrust. As an example, the vehicle following the curve 282 would have to be traveling at a rate of 1.5 feet per second at a distance of 20 feet from the dock point in order to stop just at the dock point. On the other hand, with one of the four linear induction motors on in the reverse thrust direction, the curve 284 obtains. Following this curve, for example, a vehicle traveling at a speed of 5 feet per second at a distance of 20 feet from the dock point would be stopped just at the dock point. Curves 286, 288, and 290 represent the speed-distance relationship which would obtain with two, three, and four motors, respectively, operating to produce reverse thrust. Summarizing the illustration of FIG. 13, it can be seen that a maximum deceleration rate is produced with all four motors on in the reverse direction while a minimum deceleration rate is experienced with no motors on in the reverse direction and, therefore, the time sequence of motor actuation required to stop the vehicle in a given number of feet can theoretically be determined by matching vehicle speed at the given distance to a point along one of the curves 282, 284, 286, 288, and 290 and simply energizing the number of motors

corresponding to that speed and distance to bring the vehicle to a stop at the dock point. As a practical matter, however, the speed of a given vehicle will seldom, if ever, correspond exactly with one of the intersections between the curves 282, 284, 286, 288, and 290 and the exact distance over which the precision stop function is to be accomplished. Therefore, it is necessary through the X_c computer unit 86 of FIG. 10 and a position servo loop closed through differential adder 174 of FIG. 6 to produce an adaptive control function which monitors vehicle speed and distance within the precision stop interval and switches the proper number of motors on at the proper time while at the same time minimizing the cycling of motors between off and on states.

The aforementioned objective is accomplished using the step controller 202 of FIG. 8 and the control voltage 186 which is applied thereto. The precision stop control loop operates on a command signal defined by an equation solved by computer 86 in the X_c mode. This equation or function is determined by the initial velocity of the vehicle entering the precision stop mode and the desired level of constant deceleration for this stopping maneuver ($\ddot{X}_{ps}$). As previously described, a proportional controller may also be employed.

Referring to FIG. 14, a description of a typical precision stop maneuver will be given. The quantity set by the equation mentioned above serves as a position reference quantity and is produced on a continuous basis once the precision stop wayside marker 28 is passed and related to the distance required to stop the vehicle at a constant deceleration. For example, the equation for one tested system called for a control voltage which was approximately 0.85 times the square of actual vehicle velocity.

The beginning of the precision stop phase occurs 15 feet from the desired docking point 16 and is indicated by passage of the wayside transmitter 28 which is exactly 15 feet from the dock point. Again these numbers are given purely by way of example. Thus, upon passing this marker, the stopping control equation X_c is implemented and becomes the desired position command to the vehicle 10. Assuming by reference to FIG. 14 that upon passing the marker transmitter 28 the entrance velocity is 6 feet per second. Solving the stopping equation indicates that the vehicle should be approximately 30 feet from the dock point if it were to be stopped using the implied capability of one motor from an initial velocity of 6 feet per second. Therefore, the position error is 15 feet and for typical loop gains used the step controller 202 of FIG. 7 immediately switches all four linear motors on to decelerate the vehicle. Speed decreases abruptly, as indicated in FIG. 14, until the position error factor reduces to the level required to energize only three motors. For the stopping trajectory of this example, the switch from four to three motors occurs at a distance of 12 feet from the dock point and an actual velocity of approximately 4.7 feet per second. At approximately 11.2 feet from the dock point, the error control signal has been reduced to a point that another motor is switched out of the deceleration function. At approximately 9 feet from the dock point, the vehicle has been brought into an acceptable position on the computed stopping trajectory and a single motor performs the stopping function until the vehicle position exceeds the acceptable error boundary or reaches a fixed point which is 6 inches less than the 15 foot dis-

tance to be traveled from the last wayside marker 28 to the dock point 16. At this time and position all four motors are turned on to bring the vehicle to a dead stop irrespective of the previous control function; in other words, the four linear motors are always turned on at a point which is 6 inches from the desired dock point. Again, the 6 inch figure is given only as an example of system tested and found satisfactory for experimental purposes. Moreover, it should be noted that the four-motor deceleration function is necessitated by the step control approach in that to keep cycling of motors down to a minimum, a rather low gain and, therefore, high tracking position error is required. That is illustrated by error shown in FIG. 14. The result is that the vehicle often has a rather large residual velocity which must be killed off rather severely by the four-motor deceleration in the last 6 inches. Adding a degree of proportional thrust control, the gain could be increased and, therefore the error could be reduced, this resulting in better tracking of the desired trajectory and thereby eliminating the residual velocity and the accompanying four motor deceleration.

In the example just given it can be seen that with the exception of the maximum stop function at 6 inches from the dock point 16 none of the four motors on the vehicle 10 is cycled more than once and there are actually only five steps overall in the precision stop.

In summary, the system of FIG. 3 is designed to produce an automatic vehicle speed and acceleration control function which smoothly accelerates the vehicle to a desired line velocity, determines the point at which the deceleration phase is to be entered in order to reach a docking velocity at a predetermined distance from the end of the run and to execute a precision stop maneuver which brings the vehicle to a dead stop at a docking point having very close tolerances. The system is adapted to operate in a fully automatic fashion optionally requiring the operator to establish only the acceptable limits of acceleration and jerk, the desired line speed and the location. The precision stop operation is again carried out automatically using a step control approach between the four linear motors of the vehicle by reference the relationship between actual speed and position data to a standard error quantity relationship which is derived from the relationship between distance and speed using a specific deceleration program for control. It is to be understood that various implementations may be realized of each and any of the sub-components illustrated herein and that the system may be applied to vehicles of various types including, but certainly not limited to vehicles supported by air bearings and traveling fixed boundary guideways. The foregoing specifications is thus to be construed as illustrative rather than limiting the invention.

The embodiments of the invention in which the exclusive property or privilege is claimed are defined as follows:

1. A vehicle displacement control system for effecting controlled vehicular travel between two points according to a program of velocities and velocity changes, comprising:

a vehicle adapted for displacement along the prescribed route which passes through said point five;

at least one controllable propulsion source for said vehicle;

first computer means for determining the position of said vehicle between said points and for producing a position signal;

means for producing a jerk limit signal;

means including an integrator having an input connected to receive said jerk limit signal for producing an acceleration control such that velocity changes are made within a jerk limit;

means operatively interconnected with said first computer means for producing command vehicle velocity signals at various positions along said route;

means for producing actual vehicle velocity signals;

means for producing a vehicle velocity error signal representing the difference between actual vehicle velocity and command vehicle velocity;

second computer means connected to receive said command vehicle velocity signal and said actual vehicle velocity signal for producing a jerk control signal whenever the actual vehicle velocity is at least equal to the command vehicle velocity less a predetermined vehicle velocity increment related to said jerk limit; and

mode select switch means operating under the control of said jerk control signal for selectively connecting one of said acceleration control signals, said position signal, and said vehicle velocity error signal to said controllable propulsion source for regulating the thrust thereof to produce vehicle velocity changes at predetermined times and positions, but only at such rates as are permitted by said jerk limit signal, whereby said control system operates discretely in either a position-controlled servo

loop mode, a velocity-controlled servo loop mode, or an acceleration-controlled servo loop mode, depending upon said program and the condition of said mode select switch.

2. A vehicle displacement control system as in claim 1 wherein said controllable propulsion source comprises a linear induction motor having a portion carried by said vehicle and a portion disposed along the prescribed route of said vehicle.

3. A vehicle displacement control system as in claim 1 wherein said second computer means includes analog means for determining the quantity $\dot{X}_j = \ddot{X}_0^2 / 2\ddot{X}$ where $\dot{X}_j$ is the vehicle velocity differential at which an acceleration change is effective, $\ddot{X}_0$ is the first time derivative of actual vehicle velocity, and $\ddot{X}$ is the selected rate of acceleration variation, and means for continuously comparing $\dot{X}_j$ with $\dot{X}_0$.

4. A vehicle displacement control system as in claim 3 including marker means disposed along the prescribed route at predetermined intervals.

5. A vehicle displacement control system as in claim 4 wherein said marker means are signal transmitters, the combination further comprising means carried by the vehicle for receiving signals from said signal transmitters, said lastnamed means being operatively connected with said first computer means for updating the position of said vehicle between said points.

6. A vehicle displacement control system as in claim 2 including at least a second linear induction motor for propelling the vehicle, and means for actuating the motors in such combination, and at such times, as to decelerate the vehicle to a stop in a predetermined length of said prescribed route.

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