



(51) International Patent Classification:
B61L 3/00 (2006.01) **B61L 15/00** (2006.01)

(21) International Application Number:
PCT/US2009/065734

(22) International Filing Date:
24 November 2009 (24.11.2009)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
12/277,036 24 November 2008 (24.11.2008) US
12/277,016 24 November 2008 (24.11.2008) US

(71) Applicant (for all designated States except US): **GENERAL ELECTRONIC COMPANY** [US/US]; 1 River Road, Schenectady, NY 12345 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **KALYANAM, Krishnamoorthy** [IN/US]; 2472 Heather Glen Court, Apartment 4, Beavercreek, OH 45431 (US). **HOUP, Paul, K.** [US/US]; 1050 Avon Road, Schenectady, NY 12308 (US). **SIVASUBRAMINIAM, Manthram** [IN/IN]; Cma 103, Golden Blossom Apartments, Kadugodi, Bangalore 560067 (IN). **KUMAR, Ajith** [US/US]; 528 Donna Drive, Erie, PA 16509 (US).

(74) Agents: **KRAMER, John, A.** et al.; General Electronic Company, Global Patent Operation, PO Box 861, 2 Corporate Drive, Suite 648, Shelton, CT 06484 (US).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))
- as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))

Published:

- without international search report and to be republished upon receipt of that report (Rule 48.2(g))

(54) Title: CONTROL SYSTEM AND METHOD FOR CONTROLLING MOVEMENT OF AN OFF-HIGHWAY VEHICLE

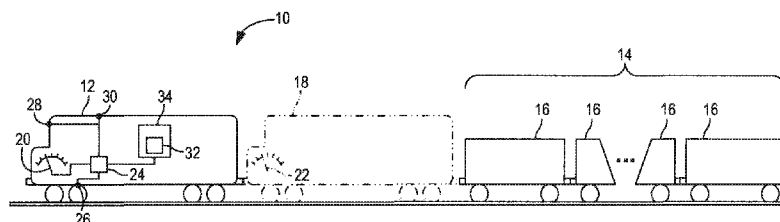


FIG. 1

(57) Abstract: A control method for controlling movement of an off-highway vehicle comprises acquiring a plurality of actual train speed measurements from at least one sensor during a journey, and acquiring a train power parameter corresponding to each of the plurality of actual train speed measurements. A plurality of resistance parameters are estimated or otherwise determined from the plurality of actual train speed measurements and the corresponding train power parameters. Movement of the off-highway vehicle (e.g., throttle commands) is based at least in part on the plurality of resistance parameters, which may be incorporated into a vehicle operation model and/or route plan according to which the vehicle is controlled.

CONTROL SYSTEM AND METHOD FOR CONTROLLING MOVEMENT OF AN OFF-HIGHWAY VEHICLE

BACKGROUND

[0001] The invention includes embodiments that relate to controlling the movement of trains or other off-highway vehicles through a determination of operational characteristics (e.g., resistance parameters, weight and weight distribution, and available power) of the train or other off-highway vehicle.

[0002] In operating a train having, for example, a plurality of vehicles providing power to move the train and another plurality of vehicles to be pulled or pushed by the powered vehicles, some of the factors that an operator or driving system may take into account include environmental conditions, track grade or slope, track or path curvature, speed limits, vehicle size, vehicle configuration, an amount of supply power available from the vehicles (both motoring and braking), weight of the train and the cargo, the distribution of that weight along the train, and the desired route and schedule for a journey.

[0003] Existing train navigation systems assume perfect knowledge of a number of the above-described operating factors and use preset estimates of the train weight and other train resistance parameters in train operation models to control the train power. However, operating a train using a static estimate of these train parameters may lead to excess fuel consumption and inaccurate speed regulation, potentially causing the train to violate speed limits. Thus, a navigation system capable of operating the train or assisting the vehicle operator may benefit from a real time estimation or other determination of train operational characteristics during a journey or trip, including available power in a train, resistance parameters of a train along a train route, and weight and weight distribution in a train, which may not be available or known prior to beginning a journey or trip. Such parameter estimates may be used to increase the accuracy of the train operation model.

[0004] It may be desirable to have a system that has aspects and features that differ from those systems that are currently available. It may be desirable to have a method that differs from those methods that are currently available.

BRIEF DESCRIPTION

[0005] Embodiments of the invention provide a control system and method for controlling movement of a train or other off-highway vehicle through an estimation or other determination of operational characteristics of the train or other off-highway vehicle.

[0006] In an embodiment, a control method for controlling an off-highway vehicle comprises acquiring a plurality of actual vehicle speed measurements from at least one sensor during a journey, and acquiring a respective vehicle power parameter corresponding to each of the plurality of actual vehicle speed measurements. The method further comprises estimating a plurality of resistance parameters from the plurality of actual vehicle speed measurements and the corresponding vehicle power parameters. Vehicle power is regulated, for controlling movement of the vehicle, based (at least in part) on the plurality of resistance parameters. For example, the resistance parameters may be incorporated into a vehicle operation model, which is used as the basis for controlling the vehicle.

[0007] In another embodiment, a control method comprises monitoring train or other off-highway vehicle operating conditions, estimating a plurality of resistance parameters based on the monitored vehicle operating conditions, accessing a trip database, and updating a vehicle operation model based on the vehicle operating conditions, the estimated plurality of resistance parameters, and the trip database. The method further comprises controlling movement of the train or other off-highway vehicle based (at least in part) on the updated vehicle operation model.

[0008] In another embodiment, a control system is implemented as part of a vehicle consist (meaning a plurality of vehicles linked to travel together) and includes a computer disposed within one of the plurality of vehicles (e.g., in a lead or command vehicle). The computer includes one or more processors configured to track a trip

schedule, monitor an operating speed of at least one of the plurality of vehicles, estimate a weight of the vehicles, estimate a plurality of vehicle resistance parameters, and update a operation model based on the trip schedule, operating speed, vehicle weight, and vehicle resistance parameters. The vehicle consist is controlled based (at least in part) on the operation model updated in this manner.

[0009] In another embodiment, a control method comprises acquiring a plurality of parameters of a train or other off-highway vehicle, the parameters including parameters measured after the vehicle has begun a journey. The off-highway vehicle includes a plurality of vehicles providing tractive effort (sometimes referred to herein as powered vehicles). The method further comprises calculating the tractive effort of less than all of the plurality of vehicles based on the acquired plurality of parameters, and controlling movement of the vehicles based on the calculated tractive effort.

[0010] Another embodiment relates to a control method for controlling a vehicle consist (e.g., train or other consist of off-highway vehicles). The vehicle consist comprises a plurality of vehicles linked to travel together, including at least one powered vehicle for moving the vehicle consist and at least one non-powered vehicle (meaning a vehicle that does not provide tractive effort.) The method comprises acquiring a plurality of parameters of the vehicle consist. The parameters are measured after the vehicle consist has begun a journey. The plurality of acquired parameters includes a plurality of tractive effort parameters of a command vehicle of the vehicle consist and a plurality of speed parameters of the vehicle consist. Each tractive effort parameter and each speed parameter is measured at a distinct time after the vehicle consist has begun the journey. The method further comprises calculating the tractive effort of less than all of the plurality of vehicles based on the acquired plurality of parameters, calculating a route plan based at least in part on the calculated tractive effort, and controlling movement of the vehicle consist based at least in part on the route plan.

[0011] In another embodiment, a method (e.g., for controlling a vehicle) comprises measuring a plurality of tractive effort values of a first powered vehicle of a vehicle consist moving along a route. The method further comprises measuring a plurality of

speed values of the vehicle consist moving along the route. The method further comprises estimating the tractive effort of one or more second powered vehicles of the vehicle consist based on the measured plurality of tractive effort values and the measured plurality of speed values.

[0012] Various other features will be apparent from the following detailed description and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The drawings illustrate embodiments contemplated for carrying out the invention. For ease of illustration, a train powered by locomotives has been identified, but other off-highway vehicles and/or vehicle consists are included except where language or context indicates otherwise.

[0014] FIG. 1 is an illustration showing a train with a control system according to an embodiment of the invention.

[0015] FIG. 2 is a flow chart illustrating a control method according to an embodiment of the invention.

[0016] FIG. 3 is an illustration showing a train with a navigation system according to an embodiment of the invention.

[0017] FIG. 4 is a flowchart illustrating a technique (control method) for determining available power and weight distribution in a train according to an embodiment of the invention.

DETAILED DESCRIPTION

[0018] The invention includes embodiments that relate to navigation systems. The invention also includes embodiments that relate to estimation of train parameters. The invention includes embodiments that relate to methods for estimating of train parameters. The invention includes embodiments that relate to methods and systems for controlling movement of off-highway vehicles and vehicle consists.

[0019] According to one embodiment of the invention, a control method for controlling an off-highway vehicle comprises acquiring a plurality of actual vehicle speed measurements from at least one sensor during a journey. The method further comprises acquiring a respective vehicle power parameter corresponding to each of the plurality of actual vehicle speed measurements. A plurality of resistance parameters is estimated from the plurality of actual vehicle speed measurements and the corresponding vehicle power parameters. Vehicle power of the vehicle is regulated to control movement of the vehicle, based at least in part on the plurality of resistance parameters.

[0020] In another embodiment, a computer readable storage medium has a sequence of instructions stored thereon, which, when executed by a processor, causes the processor to acquire a plurality of actual train (or other off-highway vehicle or vehicle consist) speed measurements from at least one sensor during a journey and acquire a train (or other off-highway vehicle or vehicle consist) power parameter corresponding to each of the plurality of actual train (or other off-highway vehicle or vehicle consist) speed measurements. The sequence of instructions further causes the processor to estimate a plurality of resistance parameters from the plurality of actual train (or other off-highway vehicle or vehicle consist) speed measurements and the corresponding train (or other off-highway vehicle or vehicle consist) power parameters.

[0021] According to one embodiment of the invention, a control method includes the steps of monitoring train (or other off-highway vehicle or vehicle consist) operating conditions, estimating a plurality of resistance parameters based on the monitored train (or other off-highway vehicle or vehicle consist) operating conditions, accessing a trip database, and updating a train (or other off-highway vehicle or vehicle consist) operation model based on the train operating conditions, the estimated plurality of resistance parameters, and the trip database.

[0022] According to another embodiment, a control system is implemented as part of a vehicle consist (as noted above, meaning a plurality of vehicles linked to travel together) and includes a computer disposed within one of the plurality of vehicles. The computer includes one or more processors configured to track a trip schedule, monitor

an operating speed of at least one of the plurality of vehicles, estimate a weight of the vehicles, estimate a plurality of vehicle resistance parameters, and update a operation model based on the trip schedule, operating speed, vehicle weight, and vehicle resistance parameters. The vehicle consist is controlled based (at least in part) on the operation model updated in this manner.

[0023] FIG. 1 shows a train 10 with a navigation/control system according to an embodiment of the invention. The train 10 includes at least one primary vehicle 12 (powered vehicle) that provides tractive effort or power to push or pull a consist 14 made up of a plurality of individual cars 16. In an embodiment of the invention, vehicle 12 is a railroad or freight locomotive; however, other off-highway vehicles and vehicle consists are contemplated. The number of locomotives 12 in train 10 may vary depending on, for example, the number of cars or vehicles 16 and the load they are carrying. As shown, train 10 includes one locomotive 12. However, as shown in phantom, one or more additional locomotives, for example locomotive 18, may be included. Cars 16 may be any of a number of different types of cars for carrying freight or passengers.

[0024] In one embodiment, one of the locomotives, for example locomotive 12, is a master or command vehicle, and any remaining locomotives, for example optional locomotive 18, are slave or trail powered vehicles. However, it is contemplated that any of the plurality of primary vehicles 12 and 18 may be the command vehicle from which the remaining trail locomotives receive commands. In this manner, an operator, engineer, or vehicle navigation/control system may control the set of locomotives 12 and 18 by controlling the command vehicle. For example, the operator or vehicle navigation system may set a throttle 20 of the master locomotive 12 to a first notch position, causing the throttle 22 of the trail vehicle 18 to move to the first notch position accordingly.

[0025] According to an embodiment of the invention, lead locomotive 12 includes a sensor system 24 connected to a number of sensors 26, 28, 30 configured to collect data related to operation of the train 10. According to an exemplary embodiment of the invention, sensor 26 may be configured to collect data corresponding to an actual speed

of the train 10, sensor 28 may be configured to collect wind speed data and/or data related to other environmental conditions, and sensor 30 may be configured to collect positional data. According to one embodiment, sensor 30 may be, for example, part of a global positioning system. It is contemplated that additional sensors may be positioned either on or within the train 10 to collect other data of interest, including, for example, the tractive effort or horsepower of lead locomotive 12. Values or parameters measured via sensor system 24 are input and read by a computer 32 configured to operate train 10 according to a plan determined in part by the estimated resistance parameters and weight of the train 10 as discussed in greater detail below. The estimates of the resistance parameters or Davis parameters may represent estimates of journal friction, a rolling resistance of an axle of the train 10, and wind resistance based on the geometry of the train 10. In an embodiment, computer 32 is part of a navigation/control system 34 configured to operate train 10 according to a train operation model. As discussed in detail below, the train operation model is derived in part using the estimates of the resistance parameters and the weight of the train 10.

[0026] Motion for the train 10, assuming the train 10 is a point mass, may be approximated using a point mass model of the form:

$$\dot{v} = \frac{P}{v} \alpha - (a + bv + cv^2) - g \quad (\text{Eqn. 1}),$$

where α represents the inverse of the weight M of the train 10. The engine power P and the train speed v represent the input and output of the system, respectively. Davis model parameters a , b , and c represent resistive coefficients resulting from resistive forces acting on the train 10, and g represents contributions due to grade or gradient.

[0027] By introducing the variables $x_1 = v$ to indicate the actual train speed and $x_2 = P$ to indicate the train power, nonlinear system dynamics are set forth of the form:

$$\begin{aligned} \dot{x}_1 &= \mathbf{f}(x_1, x_2) \theta - g \\ \dot{x}_2 &= u \end{aligned} \quad (\text{Eqn. 2}),$$

where θ is a vector of the form $\theta = [\alpha \ a \ b \ c]'$ that represents the unknown but constant resistance parameters and $\mathbf{f}(x_1, x_2)$ is a nonlinear vector function of the form

$$\mathbf{f}(x_1, x_2) = \begin{bmatrix} \frac{x_2}{x_1} - 1 - x_1 - x_1^2 \\ x_1 \end{bmatrix}.$$

[0028] The estimate of the unknown model parameters, represented by $\hat{\theta}$, is introduced by a second change of variables of the form:

$$\begin{aligned} \xi_1 &= x_1 \\ \xi_2 &= \mathbf{f}\hat{\theta} - g \end{aligned} \quad (\text{Eqn. 3}),$$

where $\hat{\theta}$ is a vector of the form $\hat{\theta} = [\hat{\alpha} \ \hat{a} \ \hat{b} \ \hat{c}]'$ and $\hat{\alpha}$, $\hat{a}$, $\hat{b}$, and $\hat{c}$ represent the estimate of the resistance parameters α , a , b , and c respectively. The time derivative of Eqn. 3 thus yields:

$$\begin{aligned} \dot{\xi}_1 &= \xi_2 + \mathbf{f}(\theta - \hat{\theta}) \\ &= \xi_2 + \mathbf{f}\hat{\theta} \\ \dot{\xi}_2 &= \dot{\mathbf{f}}\hat{\theta} + \mathbf{f}\dot{\hat{\theta}} - \dot{g} \\ &= \left(\frac{\partial \mathbf{f}}{\partial \xi_1} \dot{\xi}_1 + \frac{\partial \mathbf{f}}{\partial x_2} u \right) \hat{\theta} + \mathbf{f}\dot{\hat{\theta}} - \dot{g} \\ &= \frac{\partial \mathbf{f}}{\partial \xi_1} \hat{\theta} \dot{\xi}_1 + \frac{\partial \mathbf{f}}{\partial x_2} u + \mathbf{f}\dot{\hat{\theta}} - \dot{g} \end{aligned} \quad (\text{Eqn. 4}),$$

where $\dot{\xi}_1$, $\dot{\xi}_2$, $\dot{\mathbf{f}}$, $\dot{g}$, and $\dot{\hat{\theta}}$ represent the time derivatives of ξ_1 , ξ_2 , $\mathbf{f}$, g , and $\hat{\theta}$, respectively.

[0029] A linearizing feedback control law of the form:

$$\frac{\partial \mathbf{f}}{\partial \xi_1} u = p_2 (z - \xi_1) - \left(p_1 + \frac{\partial \mathbf{f}}{\partial \xi_1} \hat{\theta} \right) \dot{\xi}_1 - \mathbf{f}\dot{\hat{\theta}} \quad (\text{Eqn. 5}),$$

is chosen, where z represents the desired train speed, p_1 represents a first proportional-integral (PI) gain input, and p_2 represents a second PI gain input. Eqns. 4 and 5 are then combined to form a closed loop system dynamic:

$$\begin{aligned}
\dot{\xi} &= \begin{bmatrix} 0 & 1 \\ -p_2 & -p_1 \end{bmatrix} \xi + \begin{bmatrix} 1 \\ -p_1 \end{bmatrix} f\tilde{\theta} + \begin{bmatrix} 0 \\ p_2 \end{bmatrix} z \\
&= A\xi + B\tilde{\theta} + \begin{bmatrix} 0 \\ p_2 \end{bmatrix} z
\end{aligned}
\tag{Eqn. 6},$$

where $\xi = \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix}$, A represents the matrix $\begin{bmatrix} 0 & 1 \\ -p_2 & -p_1 \end{bmatrix}$, B represents the vector $\begin{bmatrix} 1 \\ -p_1 \end{bmatrix}$,

and $\tilde{\theta} = \theta - \hat{\theta}$ represents the difference between the unknown but constant resistance parameters and the estimates of the resistance parameters.

[0030] The closed loop system dynamic is associated with the transfer function from z to ξ_1 of the form:

$$G_{z \rightarrow \xi_1} = \frac{p_2}{s^2 + p_1 s + p_2} \tag{Eqn.7},$$

where s represents the Laplace variable. Eqn. 7 may be represented in state space form by:

$$\dot{\xi}_m = A\xi_m + \begin{bmatrix} 0 \\ p_2 \end{bmatrix} z \tag{Eqn. 8},$$

where ξ_m represents the state vector for the model.

[0031] The error vector is then defined as:

$$e = \xi - \xi_m \tag{Eqn. 9},$$

and is governed by:

$$\dot{e} = Ae + B\tilde{\theta} \tag{Eqn. 10}.$$

[0032] The PI gain inputs, p_1 and p_2 , are both defined as being greater than zero to create a stable system matrix A . Positive definite matrix Q is also determined, such that:

$$A'Q + QA = -I \quad (\text{Eqn. 11}),$$

where I represents the identity matrix.

[0033] Returning to Eqn. 5 and expanding the term $\frac{\partial f}{\partial \xi_1} \hat{\theta}$ results in:

$$\frac{\hat{\alpha}}{\xi_1} u - \frac{\hat{\alpha}P}{\xi_1^2} \dot{\xi}_1 = p_2 (z - \xi_1) - (p_1 - \hat{b} - 2\hat{c}\xi_1) \dot{\xi}_1 - f\hat{\theta} \quad (\text{Eqn. 12}),$$

and integrating both sides and returning the original variables yields:

$$P = \hat{M}v \left(p_2 \int (z - v) ds - (p_1 - \hat{b} - \hat{c}v) v - \int f\hat{\theta} ds \right) \quad (\text{Eqn. 13}).$$

[0034] Finally, by assuming $p_1 - \hat{b} - \hat{c}v \approx p_1$, an update law for the parameter estimates is derived of the form:

$$P = \hat{M}v \left(p_2 \int (z - v) ds - p_1 v - \int f\hat{\theta} ds \right) \quad (\text{Eqn. 14}).$$

Thus, Eqn. 14 is a variable gain scheduled PI controller with the additional contribution from $f\hat{\theta}$. When P is chosen as the control input as opposed to u , Eqn. 14 does not require the train acceleration $\dot{v}$.

[0035] Next, an update law is derived for the resistance parameter estimates that will ensure that both the resistance parameter estimation error $\tilde{\theta}$ and the speed error, which represents the difference between the desired train speed z and the actual train speed v , converge to zero.

[0036] The acceleration fit error η is then defined as:

$$\eta = \dot{\xi}_1 - \xi_2 = f\tilde{\theta} \quad (\text{Eqn. 15}),$$

which is derived in part from Eqn. 4. Next, a candidate Lyapunov function of the form:

$$\begin{aligned} V &= \frac{1}{2\gamma} \tilde{\theta}' \dot{\tilde{\theta}} \\ \Rightarrow \dot{V} &= \frac{1}{\gamma} \tilde{\theta}' \ddot{\tilde{\theta}} \end{aligned} \quad (\text{Eqn. 16}),$$

is tested for convergence, where γ is a gain parameter that is chosen to determine the rate of parameter update. A parameter update equation is also chosen of the form:

$$\begin{aligned} \dot{\tilde{\theta}} &= \gamma \mathbf{f}' \eta \\ \Rightarrow \dot{V} &= -\tilde{\theta}' \mathbf{f}' \mathbf{f} \tilde{\theta} \\ &= -\eta^2 \end{aligned} \quad (\text{Eqn. 17}).$$

The Lyapunov function of Eqn. 16 is negative as long as η is not equal to zero. Since V is greater than or equal to zero, the fit error η will necessarily go to zero.

[0037] Eqn. 15 and Eqn. 17 may be combined to form:

$$\dot{\tilde{\theta}} = -\dot{\tilde{\theta}} = -\gamma \mathbf{f}' \mathbf{f} \tilde{\theta} \quad (\text{Eqn. 18}).$$

Eqn. 18 satisfies the parameter convergence condition that the parameter estimation error $\tilde{\theta}$ goes to zero. Eqn. 18 also satisfies the convergence condition that the speed error goes to zero. From the speed error dynamics (Eqn. 10), when the input parameter estimation error $\tilde{\theta}$ goes to zero the speed error also goes to zero since A is a stable matrix. Thus, Eqn. 18 satisfies convergence of both the resistance parameter estimation error and the speed error.

[0038] The control law becomes:

$$P = \hat{M}v (p_2 \int (z - v) ds - p_1 v - \gamma \int \mathbf{f}' \eta ds) \quad (\text{Eqn. 19}).$$

[0039] Next, the actual train speed v is numerically differentiated to determine the train acceleration $\dot{v}$, which is used in both the update equation (Eqn. 17) and the control law (Eqn. 19).

[0040] Because the prescribed update method requires numerical differentiation of the actual train speed v , errors are introduced in the system. These errors are

particularly prevalent when the train speed signal is noisy. To address this signal noise, the fit error of Eqn. 15 is multiplied by the actual train speed v and redefined as:

$$\eta = v\dot{v} - P\hat{\alpha} + (\hat{a}v + \hat{b}v^2 + \hat{c}v^3) + gv \quad (\text{Eqn. 20}).$$

[0041] A trapezoidal discretization converts the continuous time equation of Eqn. 20 to:

$$\left(\frac{v_{k+1}+v_k}{2}\right) \left(\frac{v_{k+1}-v_k}{\delta t}\right) - \eta_k = \frac{P_{k+1}\hat{\alpha} - \hat{a}v_{k+1} - \hat{b}v_{k+1}^2 - \hat{c}v_{k+1}^3 - g_{k+1}v_{k+1}}{2} + \frac{P_k\hat{\alpha} - \hat{a}v_k - \hat{b}v_k^2 - \hat{c}v_k^3 - g_kv_k}{2} \quad (\text{Eqn. 21}),$$

where δt represents sampling time. Eqn. 21 is then manipulated as:

$$\frac{v_{k+1}^2 - v_k^2}{\delta t} + g_{k+1}v_{k+1} + g_kv_k = (P_{k+1} + P_k)\hat{\alpha} - (v_{k+1} + v_k)\hat{a} - (v_{k+1}^2 + v_k^2)\hat{b} - (v_{k+1}^3 + v_k^3)\hat{c} + \eta_k \quad (\text{Eqn. 22}).$$

Collecting all unknowns on one side results in:

$$\left[P_{k+1} + P_k - v_{k+1} - v_k - v_{k+1}^2 - v_k^2 - v_{k+1}^3 - v_k^3 \right] \hat{\theta} = \frac{v_{k+1}^2 - v_k^2}{\delta t} + \eta_k + g_{k+1}v_{k+1} + g_kv_k \\ \Rightarrow \phi_k \hat{\theta} = y_k + \eta_k \quad (\text{Eqn. 23}),$$

where $\phi_k = [P_{k+1} + P_k - v_{k+1} - v_k - v_{k+1}^2 - v_k^2 - v_{k+1}^3 - v_k^3]$ and

$y_k = \frac{v_{k+1}^2 - v_k^2}{\delta t} + g_{k+1}v_{k+1} + g_kv_k$. The n data points are stacked to form a regressor vector

$\Phi = [\phi_1 \cdots \phi_n]'$ and an output vector $Y = [y_1 \cdots y_n]'$, resulting in the matrix relation:

$$\Phi\theta = Y + \eta \quad (\text{Eqn. 24}).$$

[0042] As before, the estimation problem may be posed as the least squares minimization problem:

$$\min_{\theta} |\eta|^2 = \min_{\theta} (\Phi\theta - Y)'(\Phi\theta - Y) \quad (\text{Eqn. 25}),$$

and with the solution given by:

$$\hat{\theta} = (\Phi' \Phi)^{-1} \Phi' Y \quad (\text{Eqn. 26}).$$

A solution for Eqn. 26 exists if the data matrix has full rank, i.e.

$$\Phi' \Phi > 0 \quad (\text{Eqn. 27}).$$

[0043] Eqn. 26 represents a batch least squares solution. Therefore, a recursive least squares form of the form:

$$\begin{aligned} e_k &= y_k - \phi_k' \hat{\theta}_{k-1} \\ \Pi_k &= \left(I - \frac{\Pi_{k-1} \phi_k' \phi_k}{\lambda + \phi_k' \Pi_{k-1} \phi_k} \right) \frac{\Pi_{k-1}}{\lambda} \\ \hat{\theta}_k &= \hat{\theta}_{k-1} + \frac{\Pi_{k-1} \phi_k'}{\lambda + \phi_k' \Pi_{k-1} \phi_k} e_k \end{aligned} \quad (\text{Eqn. 28}).$$

In Eqn. 28, e denotes the model fit error and I is the identity matrix. The covariance matrix Π is initialized to $\Pi_0 = \frac{1}{\delta} I$, where δ is taken to be a small positive number. The forgetting factor λ is chosen such that $0 < \lambda \leq 1$.

[0044] According to embodiments of the invention, train speed may be controlled according to a technique 36 (control method) as illustrated in FIG. 2. Technique 36 monitors operating conditions of the train 10 of FIG. 1 during a journey and continuously updates a train operation model based on the monitored operating conditions. According to an exemplary embodiment of the invention, the updated train operation model optimizes driving commands such as train speed and train power, thus maximizing fuel consumption and minimizing the train speed error.

[0045] Technique 36 begins at step 38 by loading a trip request into the navigation system 34 of FIG. 1. The trip request may include such trip information as the trip destination, a desired trip time and/or limits on the trip time, location and duration of

stops along the journey, information regarding the train manifest such as load and consist information, route information, speed limits corresponding to the route, and the like. The train journey begins at step 40, after power is applied to the primary locomotive 12 of FIG. 1. At step 42 one or more of the sensors 26, 28, 30 of FIG. 1 acquire data relating to train operating conditions, for example, the actual train speed, train power, and train position. Technique 36 then estimates a train weight and train resistance parameters 44 using the train operating condition data acquired at step 42. At step 46, the trip database is consulted to access trip information, such as a desired train speed, corresponding to the determined position of the train 10.

[0046] Technique 36 next uses the actual train speed and power data, estimated train weight and resistance parameters, and the trip information to determine a train resistance parameter error at step 48. At step 50, the train resistance parameter error is analyzed to determine whether it falls within a pre-selected tolerance. If the parameter error does fall within the desired tolerance range 52, the train operation model is updated at step 54 with the estimates of train weight and train resistance parameters obtained at step 44. Technique 36 then enters an optional time delay 56 before returning to step 42 to reacquire train speed and power data.

[0047] If at step 50, the parameter error does not fall within the desired tolerance range 58, technique 36 proceeds to step 60 where new estimates for the train weight and resistance parameters are selected. The trip database is then selected at step 46, and the parameter error of the new parameter estimates is again determined at step 48. If, at step 50, the parameter error is within the selected tolerance 52, the navigation mode is updated at step 54. If not 58, technique 36 continues to cycle through steps 60, 46, 48, and 50 until the parameter error falls within the desired tolerance range.

[0048] In this fashion, technique 36 forms a closed-loop system that continuously estimates train model parameters, including train weight and train resistance parameters, in order to update the train operation model and optimize train power and speed regulation throughout a journey.

[0049] In another embodiment, a computer readable storage medium has a sequence of instructions stored thereon, which, when executed by a processor, causes the processor to acquire a plurality of actual train (or other off-highway vehicle or vehicle consist) speed measurements from at least one sensor during a journey and acquire a train (or other off-highway vehicle or vehicle consist) power parameter corresponding to each of the plurality of actual train (or other off-highway vehicle or vehicle consist) speed measurements. The sequence of instructions further causes the processor to estimate a plurality of resistance parameters from the plurality of actual train (or other off-highway vehicle or vehicle consist) speed measurements and the corresponding train (or other off-highway vehicle or vehicle consist) power parameters.

[0050] As noted above, the invention also includes embodiments that relate to navigation systems and related control methods.

[0051] One embodiment of the invention relates to a control method for controlling a vehicle consist (e.g., train or other off-highway vehicle). The vehicle consist comprises a plurality of vehicles linked to travel together, including at least one powered vehicle for moving the vehicle consist and at least one non-powered vehicle (meaning a vehicle that does not provide tractive effort.) The method comprises acquiring a plurality of parameters of the vehicle consist. The parameters are measured after the vehicle consist has begun a journey. The plurality of acquired parameters includes a plurality of tractive effort parameters of a command vehicle of the vehicle consist and a plurality of speed parameters of the vehicle consist. Each tractive effort parameter and each speed parameter is measured at a distinct time after the vehicle consist has begun the journey. The method further comprises calculating the tractive effort of less than all of the plurality of vehicles based on the acquired plurality of parameters, calculating a route plan based at least in part on the calculated tractive effort, and controlling movement of the vehicle consist based at least in part on the route plan.

[0052] In another embodiment, a method (e.g., for controlling a vehicle) comprises measuring a plurality of tractive effort values of a first powered vehicle of a vehicle consist moving along a route. The method further comprises measuring a plurality of speed values of the vehicle consist moving along the route. The method further

comprises estimating the tractive effort of one or more second powered vehicles of the vehicle consist based on the measured plurality of tractive effort values and the measured plurality of speed values.

[0053] According to one embodiment of the invention, a navigation system includes a computer readable storage medium having a sequence of instructions stored thereon, which, when executed by a processor, causes the processor to acquire a plurality of parameters of a train comprising parameters measured after the train has begun a journey. The train includes a plurality of vehicles providing tractive effort and a consist coupled to the plurality of vehicles. The sequence of instructions also causes the processor to calculate the tractive effort of less than all of the plurality of vehicles based on the acquired plurality of parameters.

[0054] According to one embodiment of the invention, a system includes a first plurality of vehicles coupled together and a second plurality of vehicles coupled together and coupled to the first plurality of vehicles. The second plurality of vehicles is configured to provide tractive effort to move the first plurality of vehicles and includes a primary vehicle and at least one secondary vehicle. The system further includes a computer having one or more processors programmed to measure a plurality of parameters of the primary vehicle while the second plurality of vehicles is providing tractive effort and calculate the tractive effort of the at least one secondary vehicle based on the measured plurality of parameters of the primary vehicle.

[0055] According to one embodiment of the invention, a method includes measuring a plurality of tractive effort values of a lead locomotive of a train moving along a route and measuring a plurality of speed values of the train moving along the route. The method also includes estimating the tractive effort of one or more trail locomotives of the train based on the measured plurality of tractive effort values and the measured plurality of speed values.

[0056] FIG. 3 shows a train 100 with a navigation system according to an embodiment of the invention. The train 100 includes a plurality of powered vehicles 102, 104 that provide tractive effort or power to push or pull or slow a sub-consist 106.

Powered vehicles 102, 104 provide motoring tractive effort and braking tractive effort including dynamic braking and air braking. In an embodiment of the invention, powered vehicles 102, 104 are railroad locomotives; however, other vehicles and train types are contemplated. The number of locomotives 102, 104 in train 100 may vary depending on, for example, the number of cars or vehicles 108 in sub-consist 106 and the load they are carrying. As shown, train 100 includes two locomotives 102, 104. However, as shown in phantom, additional locomotives 20 may be included. Cars 108 may be any of a number of different types of cars for carrying freight or passengers.

[0057] In one embodiment, one of the locomotives, for example, locomotive 102, is a master or command vehicle, and the remaining locomotives, for example, locomotive 104 and locomotives 120 if included, are slave or trail vehicles. In this manner, an operator or engineer or vehicle navigation system may control the set of locomotives 102-104, 120 by controlling the command vehicle. For example, the operator or vehicle navigation system may set a throttle 122 of locomotive 102 to a first notch position, and the throttles 124, 126 of the trail vehicles 104, 120 move to the first notch position accordingly. As shown, locomotive 102 is the lead locomotive and may be the command vehicle. However, it is contemplated that any of the plurality of powered vehicles 102-104, 120 may be the command vehicle from which the remaining trail locomotives receive commands. The locomotives may be positioned anywhere in the train such as at the front of the sub-consist 106, between groups of cars 108 of the consist 106, or at an back of sub-consist 106.

[0058] According to an embodiment of the invention, lead locomotive 102 includes a sensor system 128 configured to measure a speed of train 100 and the tractive effort or horsepower of lead locomotive 102. Values or parameters measured via a sensor system 128 are input and read by a computer 130 for determination of available power and weight distribution of train 100 as discussed in greater detail below. In an embodiment, computer 130 is part of a navigation system 132 configured to operate train 100 according to a plan determined in part by the determined available power and weight distribution of train 100.

[0059] Similar to Equation 1 above, motion for the train, assuming it is a point mass, may be approximated using a point mass model of the form:

$$\dot{v} = \frac{P}{v} \alpha - (a + bv + cv^2) - g \quad (\text{Eqn. 31}),$$

where α represents the inverse of the weight M of the train. The engine power P and the train speed v represent the input and output of the system, respectively. Davis model parameters a , b , and c represent train resistance, and g represents contributions due to grade or gradient.

[0060] According to an embodiment of the invention, horsepower for the trail vehicles or locomotives is to be estimated at different throttle notch settings after the train has begun a journey or trip along a route. Estimation of the trail horsepower is performed when the trail horsepower is not known or has not been identified before the trip. At each time instant, k , the horsepower of the lead locomotive, P_k^l , and the train speed, v_k , are available through measurements taken during the trip. Terrain information is also captured and represented by the gradient variable, g_k . Using this information, horsepower of the trail locomotives may be estimated.

[0061] To simplify estimation of the trail locomotive horsepower, the trail locomotives are held at a particular notch setting. This helps to ensure that the horsepower generated by the trail locomotives will be a constant and, therefore, easier to estimate. The lead locomotive need not necessarily be held at a constant notch or at the same notch position as the trail locomotives. Once an estimation of the trail horsepower for a particular notch has been completed, the notch of the trail locomotives may be moved to a different position, and estimation of the trail horsepower for the new notch position may be completed. In this manner, the trail horsepower for all notch settings may be determined according to embodiments of the invention.

[0062] The continuous time train model of Eqn. 31 having power P split into two parts results in the equation:

$$\begin{aligned} \dot{v} &= \frac{P^l + P^t}{v} \alpha - (a + bv + cv^2) - g \\ \Rightarrow v\dot{v} &= P^l \alpha + P^t \alpha - (av + bv^2 + cv^3) - gv \end{aligned} \quad (\text{Eqn. 32}),$$

where the superscripts l and t represent the horsepower of the command or lead locomotive and of the remaining or trail locomotives, respectively. The train mass and the Davis coefficients are acquired from known values.

[0063] The continuous time train model of Eqn. 32 is converted to a discrete time equivalent model because data is available at discrete time instants. For this conversion, a trapezoidal discretization method is used that results in the discrete time model:

$$\begin{aligned} \left(\frac{v_{k+1} + v_k}{2} \right) \left(\frac{v_{k+1} - v_k}{\delta t} \right) &= \frac{P^t \alpha + P_{k+1}^l \alpha - av_{k+1} - bv_{k+1}^2 - cv_{k+1}^3 - g_{k+1} v_{k+1}}{2} \\ &+ \frac{P^t \alpha + P_k^l \alpha - av_k - bv_k^2 - cv_k^3 - g_k v_k}{2} \end{aligned} \quad (\text{Eqn. 33}).$$

Collecting terms with P^t results in the data model:

$$\begin{aligned} 2P^t \alpha &= \frac{v_{k+1}^2 - v_k^2}{\delta t} + g_{k+1} v_{k+1} + g_k v_k - (P_{k+1}^l + P_k^l) \alpha \\ &+ (v_{k+1} + v_k) a \\ &+ \left(v_{k+1}^2 + v_k^2 \right) b \\ &+ \left(v_{k+1}^3 + v_k^3 \right) c \end{aligned} \quad (\text{Eqn. 34}).$$

[0064] All of the known values on the right-hand side of Eqn. 34 are denoted by the variable y_k . That is, α represents the inverse of the weight of the train; k represents a time point; P_k^l represents a measured tractive effort parameter of the command vehicle; v represents a measured speed of the train; δt represents a time difference between k and $k+1$; a , b , and c represent train resistance parameters; and g represents a grade parameter. A perfect knowledge of model parameters of Eqn. 34 results in the equation:

$$2P^t \alpha = y_k \quad \forall k \quad (\text{Eqn. 35}).$$

However, because of modeling or observation errors, a best estimate of trail horsepower $\hat{P}_t$ is calculated that will minimize the sum of squared errors $\sum_1^n \eta_k^2$ where $\eta_k = 2\hat{P}_t\alpha - y_k$. The best estimate has the simple average given by:

$$\hat{P}_t = \frac{1}{2\alpha n} \sum_1^n y_k \quad (\text{Eqn. 36}).$$

[0065] A running equation may be used instead of Eqn. 36. The running equation may be used where storing data in computer memory of y_k for all k is not desired. The running average formulation may be defined as:

$$\hat{P}_{k+1}^t = \frac{1}{k+1} \left(\hat{P}_k^t k + \frac{y_{k+1}}{2\alpha} \right) \quad (\text{Eqn. 37}).$$

Hence, the previous best estimate $\hat{P}_k^t$ and the current data y_{k+1} may be used to determine the new estimate $\hat{P}_{k+1}^t$.

[0066] Different cars in the train might be loaded or empty. Accordingly, the weight distribution of the train may not be uniform throughout. The non-uniform weight distribution has implications in terms of train handling and braking. Therefore, estimation of the weight distribution along the length of the train is desired. For this, it is assumed that the total horsepower generated by all of the locomotives P_k is available at any time instant.

[0067] The lumped train model found in Eqn. 31 is an approximation of the true train. This model is expanded to account for the resistance seen by each car and locomotive such that the dependence on the weight of each of these units is brought out.

[0068] The Davis parameters for a given unit, such as a car or locomotive of the train, may be defined as:

$$\begin{aligned} A &= d_a + d_b \frac{n}{w} \\ B &= d_c \\ C &= d_d \frac{a}{w} \end{aligned} \quad (\text{Eqn. 38}),$$

where n is the number of axles in the unit; a is a cross-sectional area of the unit; d_a , d_b , d_c , and d_d are constants that depend on the unit; and w is the weight of the unit. Recalling Eqn. 31, the lumped train model is:

$$\dot{v} = \frac{P}{v} \alpha - (a + bv + cv^2) - g \quad (\text{Eqn. 39}),$$

where the lumped Davis parameters are weighted averages of the individual unit or car/locomotive parameters.

[0069] Accordingly, the Davis parameters may be written as:

$$\begin{aligned} a &= \left(d_a^l + d_b^l \frac{n^l}{w^l} \right) (m+1) w^l \alpha + \sum_{i=1}^N \left(d_a^c + d_b^c \frac{n^c}{w_i^c} \right) w_i^c \alpha \\ b &= d_c^l (m+1) w^l \alpha + \sum_{i=1}^N d_c^c w_i^c \alpha \\ c &= \left(d_d^l a^l + m d_d^t a^t + \sum_{i=1}^N d_d^c a_i^c \right) \alpha \end{aligned} \quad (\text{Eqn. 40}),$$

where w^l denotes the weight of a vehicle or locomotive and w_i^c denotes the weight of the i^{th} car of the consist. The effective grade g may be written as a weighted average of the individual grade seen by each unit:

$$g = \left(\sum_{j=1}^{m+1} g_j^l w^l + \sum_{i=1}^N g_i^c w_i^c \right) \alpha \quad (\text{Eqn. 41}),$$

where the superscripts l , t , and c denote lead locomotive, trail locomotive, and car, respectively.

[0070] Referring to Eqn. 40, it is noted that c is independent of the unit weights. Collecting the terms in a and c that are independent of weights, w , results in:

$$\begin{aligned} \bar{a} &= d_b^l n^l (m+1) + d_b^c n^c N \\ \bar{c} &= d_d^l a^l + m d_d^t a^t + \sum_{i=1}^N d_d^c a_i^c \end{aligned} \quad (\text{Eqn. 42}),$$

where m and N are the number of trail locomotives and cars, respectively. Substituting for a , b , and c from Eqn. 40 into Eqn. 39 and multiplying both sides by v , results in the distributed train model:

$$\begin{aligned}
 v\dot{v} = & (P - \bar{a}v - \bar{c}v^3) \alpha \\
 & - \left(d_a^l v + d_c^l v^2 \right) (m+1) w^l \alpha \\
 & - \sum_{j=1}^{m+1} g_j^l v w^l \alpha \\
 & - \sum_{i=1}^N \left(d_a^c v + d_c^c v^2 + g_i^c v \right) w_i^c \alpha
 \end{aligned} \tag{Eqn. 43}.$$

[0071] Using trapezoidal discretization with sampling time δt , Eqn. 43 can be converted into the discrete time model:

$$\begin{aligned}
 (v_{k+1} + v_k) \left(\frac{v_{k+1} - v_k}{\delta t} \right) = & \left(P_{k+1} - \bar{a}v_{k+1} - \bar{c}v_{k+1}^3 \right) \alpha \\
 & - \left(d_a^l v_{k+1} + d_c^l v_{k+1}^2 \right) (m+1) w^l \alpha \\
 & - \sum g_{j,k+1}^l v_{k+1} w^l \alpha \\
 & - \sum \left(d_a^c v_{k+1} + d_c^c v_{k+1}^2 + g_{i,k+1}^c v_{k+1} \right) w_i^c \alpha \\
 & + \left(P_k - \bar{a}v_k - \bar{c}v_k^3 \right) \alpha \\
 & - \left(d_a^l v_k + d_c^l v_k^2 \right) (m+1) w^l \alpha \\
 & - \sum g_{j,k}^l v_k w^l \alpha \\
 & - \sum \left(d_a^c v_k + d_c^c v_k^2 + g_{i,k}^c v_k \right) w_i^c \alpha
 \end{aligned} \tag{Eqn. 44},$$

where k denotes the time index. Assuming that the mass of a locomotive w^l is known and having the constraint that the consist and the load mass have to add up to the train mass, i.e.,

$$\begin{aligned}
 (m+1) w^l + \sum w_i^c & = M \\
 \Rightarrow (m+1) w^l \alpha + \sum w_i^c \alpha & = 1
 \end{aligned} \tag{Eqn. 45},$$

A substitution for $w^l \alpha$ in Eqn. 44 results in the data model:

$$\begin{aligned}
& \frac{v_{k+1}^2 - v_k^2}{\delta t} + d_a^l v_{k+1} + d_c^l v_{k+1}^2 + \bar{g}_{k+1}^l v_{k+1} + \bar{g}_k^l v_k \\
& = \left(P_{k+1} - \bar{a} v_{k+1} - \bar{c} v_{k+1}^3 \right) \alpha \\
& + \left(d_a^l v_{k+1} + d_c^l v_{k+1}^2 \right) \sum w_i^c \alpha \\
& - \sum \left(d_a^c v_{k+1} + d_c^c v_{k+1}^2 + g_{i,k+1}^c v_{k+1} \right) w_i^c \alpha \\
& + \left(P_k - \bar{a} v_k - \bar{c} v_k^3 \right) \alpha \\
& + \left(d_a^l v_k + d_c^l v_k^2 \right) \sum w_i^c \alpha \\
& - \sum \left(d_a^c v_k + d_c^c v_k^2 + g_{i,k}^c v_k \right) w_i^c \alpha \\
& + \left(\bar{g}_{k+1}^l v_{k+1} + \bar{g}_k^l v_k \right) \sum w_i^c \alpha
\end{aligned} \tag{Eqn. 46},$$

where $\bar{g}_k^l = \frac{1}{m+1} \sum_{j=1}^{m+1} g_{j,k}^l$ denotes the grade averaged over the locomotives.

[0072] The data model of Eqn. 46 can be used to define the fit error:

$$\eta_k = \hat{\theta} \phi_k - y_k,$$

where the unknown vector $\theta = [\alpha \ w_1^c \alpha \ \dots \ w_Q^c \alpha]$ and $\hat{\theta}$ denotes its best estimate, where Q denotes the number of subdivisions of the train for estimating the weight distribution, where

$$y_k = \frac{v_{k+1}^2 - v_k^2}{\delta t} + d_a^l v_{k+1} + d_c^l v_{k+1}^2 + \bar{g}_{k+1}^l v_{k+1} + \bar{g}_k^l v_k, \text{ and where}$$

$$\phi_k = \begin{bmatrix} P_k + P_{k+1} - \bar{a}(v_k + v_{k+1}) - \bar{c}(v_k^3 + v_{k+1}^3) \\ (d_a^l - d_a^c)(v_k + v_{k+1}) + (d_c^l - d_c^c)(v_k^2 + v_{k+1}^2) + (\bar{g}_k^l - g_{1,k}^c)v_k + (\bar{g}_{k+1}^l - g_{1,k+1}^c)v_{k+1} \\ \vdots \end{bmatrix}$$

[0073] Supposing that there are r such data points, then the data points can be stacked to get the regressor vector $\Phi = [\phi_1 \ \dots \ \phi_r]$ and the output vector $Y = [y_1 \ \dots \ y_r]$. η represents an error vector $[\eta_1 \ \dots \ \eta_r]$. This results in the matrix relation:

$$\theta \Phi = Y + \eta \tag{Eqn. 47}.$$

[0074] Again, the estimation problem can be posed as the quadratic programming problem:

$$\begin{aligned}
& \min_{\theta} (Y - \theta\Phi) (Y - \theta\Phi)' \\
& \Rightarrow \min_{\theta} \theta\Phi\Phi'\theta' - 2Y\Phi'\theta' \\
& \Rightarrow \min_{\theta} \frac{1}{2}\theta H\theta' + f\theta'
\end{aligned}
\tag{Eqn. 48},$$

where $H = 2\Phi\Phi'$ and $f = -2Y\Phi'$, subject to the linear constraints that the sum of weights of all units should equal the total train weight,

$$\begin{bmatrix} (m+1)w^l & 1 & \dots & 1 \end{bmatrix} \theta' = 1
\tag{Eqn. 49},$$

and that the individual car weights should be greater than the weight of an empty car,

$$\begin{aligned}
& w_i^c \geq w_e \\
\Rightarrow w_e\alpha - w_i^c\alpha & \leq 0, \quad i = 1 \dots N
\end{aligned}
\tag{Eqn. 50},$$

where w_e is the weight of an empty car.

[0075] FIG. 4 shows a technique 134 for determining available power and weight distribution in a train according to an embodiment of the invention. In an embodiment, technique 134 may be programmed into computer 130 of train 100 shown in of FIG. 3 or may be stored on a computer readable storage medium readable via computer 130 such that a processor (not shown) of computer 130 may be caused to perform technique 134. In an embodiment of the invention, the computer readable storage medium may be, for example, floppy disk drives, tape drives, CD-ROM drives, DVD-RW drives, external and internal hard drives, flash drives, and the like.

[0076] Once a train, such as train 100 of FIG. 3, has begun a journey along a route, technique 134 may be performed to estimate the tractive effort or horsepower of trail vehicles are locomotives and to estimate a weight distribution along the train such that a route plan may be calculated to optimize fuel efficiency used by the train during the journey. Accordingly, a navigation system may use the route plan to automatically operate the train through to a destination of the train. Alternatively, the route plan may be used to assist an engineer operating the train to increase or maximize fuel efficiency of the train's operation.

[0077] According to an embodiment of the invention, technique 134 includes setting the trail vehicles to a notch value at step 136. Setting the trail vehicles to the same notch value allows calculation of their tractive effort at that notch value. It is contemplated that technique 134 may be performed for each notch value for which it is desirable to calculate the tractive effort of the trail vehicles. Technique 134 includes acquiring the tractive effort of the command or lead vehicle at step 138 and acquiring a speed of the train at step 140. The lead vehicle tractive effort and the train speed are accordingly acquired after the train has begun the journey. Technique 134 also includes acquiring other train parameters at step 142. The other parameters include parameters such as the Davis parameters, grade or gradient parameters, and a mass of the train. These other train parameters may be acquired from stored values determined or calculated before or after the train has begun the journey. Acquiring other train parameters 134 also includes acquiring a previously-calculated tractive effort estimation of the trail vehicles if available.

[0078] Once the lead vehicle tractive effort, train speed, and other parameters are acquired, technique 134 calculates the tractive effort or horsepower of the trail vehicles at step 144. Calculation of the trail vehicle tractive effort includes calculating or estimating the tractive effort according to the equations described above. That is, the trail vehicle tractive effort may be estimated via Eqns. 36 or 37, for example. After the tractive effort of the trail vehicles has been calculated, the tractive effort of all the vehicles may be determined at step 146. The tractive effort of all the vehicles may be used in combination with the equations described above to calculate a weight distribution of the train at step 148. The weight distribution may be calculated, for example, via Eqn. 48 subject to the constraints identified in Eqn. 49.

[0079] A technical contribution for the disclosed method and apparatus is that it provides for a computer-implemented estimation of train resistance parameters and weight of a train.

[0080] Any instances of “train” herein are not limited to train rail vehicles per se, but instead the term train includes any vehicle consist (plurality of vehicles that are linked to travel together), unless otherwise explicitly specified. Depending on the context,

certain embodiments may be applicable to off-highway vehicles generally, e.g., applicable to a single off-highway vehicle. The term “locomotive” is not meant to be limited to a train/rail locomotive, but instead encompasses powered off-highway vehicles generally, “powered” referring to an off-highway vehicle that is capable of self-propulsion, unless otherwise explicitly specified. The term “car” refers to a non-powered or unpowered off-highway vehicle, meaning a vehicle that is not capable of self-propulsion, unless otherwise explicitly specified.

[0081] While the invention has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the invention is not limited to such disclosed embodiments. Rather, the invention can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the invention. Additionally, while various embodiments of the invention have been described, it is to be understood that aspects of the invention may include only some of the described embodiments. Accordingly, the invention is not limited by the foregoing description, but is only limited by the scope of the appended claims.

WHAT IS CLAIMED IS:

1. A control method for controlling an off-highway vehicle comprising:
 - acquiring a plurality of actual vehicle speed measurements from at least one sensor during a journey;
 - acquiring a respective vehicle power parameter corresponding to each of the plurality of actual vehicle speed measurements;
 - estimating a plurality of resistance parameters from the plurality of actual vehicle speed measurements and the corresponding vehicle power parameters; and
 - regulating vehicle power of the vehicle to control movement of the vehicle based at least in part on the plurality of resistance parameters.
2. The control method of claim 1 wherein the vehicle power is regulated using a proportional integral control technique.
3. The control method of claim 1 further comprising:
 - accessing trip information from a trip schedule;
 - from the trip information, acquiring a desired vehicle speed corresponding to a current position of the vehicle;
 - carrying out a comparison of the plurality of actual vehicle speed measurements to the desired vehicle speed;
 - determining a speed error from the comparison; and
 - controlling the vehicle to minimize or reduce the speed error.
4. The control method of claim 1 further comprising:
 - defining a data collection time interval corresponding to a period of time after the vehicle has begun the journey;
 - defining a plurality of data collection times within the data collection time interval; and
 - acquiring one of the plurality of actual vehicle speed measurements in each of the plurality of data collection times.

5. The control method of claim 1 further comprising:
re-estimating the plurality of resistance parameters throughout the journey.

6. The control method of claim 1 wherein vehicle power is regulated in accordance with:

$$P = \hat{M}v(p_2 \int (z - v) ds - p_1 v - \gamma \int \mathbf{f}' \eta ds)$$

where:

P represents the vehicle power; $\hat{M}$ represents the estimate of vehicle mass; p_1 represents a first PI gain input; p_2 represents a second PI gain input; z represents the desired vehicle speed; v represents the actual vehicle speed; γ represents a gain parameter; η represents an acceleration fit error; $\mathbf{f}$ represents a nonlinear vector function; and s represents a laplace variable.

7. A method comprising:
monitoring vehicle operating conditions of an off-highway vehicle;
estimating a plurality of resistance parameters based on the monitored vehicle operating conditions;
accessing a trip database;
updating a vehicle operation model based on the vehicle operating conditions, the estimated plurality of resistance parameters, and the trip database; and
controlling movement of the vehicle based on the vehicle operation model.

8. The method of claim 7 wherein monitoring vehicle operating conditions comprises monitoring a vehicle speed and an actual vehicle power.

9. The method of claim 7 wherein updating the vehicle operation model comprises updating a desired vehicle power.

10. The method of claim 7 wherein accessing the trip database comprises determining a desired vehicle speed.

11. The method of claim 7 wherein estimating the plurality of resistance parameters comprises estimating a vehicle mass and a plurality of Davis coefficients.

12. The method of claim 11 wherein estimating the plurality of Davis coefficients comprises estimating at least one of a journal friction, a frictional coefficient, and a wind resistance.

13. The method of claim 7 wherein estimating the plurality of resistance parameters comprises implementing a least squares minimization technique.

14. The method of claim 7 further comprising:
determining a vehicle resistance parameter error;
determining whether the vehicle resistance parameter error is within a desired tolerance; and
updating the operation model if the vehicle resistance parameter error is within the desired tolerance.

15. A control method for controlling a vehicle consist comprising:
acquiring a plurality of parameters of the vehicle consist, the parameters being measured after the vehicle consist has begun a journey, wherein the vehicle consist comprises a plurality of vehicles linked to travel together, the plurality of vehicles including at least one powered vehicle for moving the vehicle consist and at least one non-powered vehicle, and wherein the plurality of acquired parameters includes a plurality of tractive effort parameters of a command vehicle of the vehicle consist and a plurality of speed parameters of the vehicle consist, each tractive effort parameter and each speed parameter measured at a distinct time after the vehicle consist has begun the journey;

calculating the tractive effort of less than all of the plurality of vehicles based on the acquired plurality of parameters;

calculating a route plan based at least in part on the calculated tractive effort;
and
controlling movement of the vehicle consist based at least in part on the route plan.

16. The method of claim 15 comprising calculating the tractive effort of the plurality of vehicles less the command vehicle.

17. The method of claim 16 wherein the plurality of acquired parameters includes a mass of the vehicle consist, a plurality of vehicle consist resistance parameters, and a plurality of grade parameters.

18. The method of claim 17 wherein the tractive effort of the plurality of vehicles less the lead vehicle is calculated in accordance with:

$$\hat{P}_{k+1}^t = \frac{1}{k+1} \left(\hat{P}_k^t k + \frac{y_{k+1}}{2\alpha} \right),$$

where:

$\hat{P}_{k+1}^t$ represents a current estimate of horsepower of the plurality of vehicles less the command vehicle; $\hat{P}_k^t$ represents a previous best estimate of the horsepower; α represents the inverse of the weight of the vehicle consist; k represents a time point;

$$\begin{aligned} y_k \text{ represents } & \frac{v_{k+1}^2 - v_k^2}{\delta t} + g_{k+1}v_{k+1} + g_kv_k - (P_{k+1}^l + P_k^l)\alpha \\ & + (v_{k+1} + v_k)a \\ & + \left(v_{k+1}^2 + v_k^2 \right)b \\ & + \left(v_{k+1}^3 + v_k^3 \right)c \end{aligned} ;$$

P_k^l represents a measured tractive effort parameter of the command vehicle; v represents a measured speed of the vehicle consist; δt represents a time difference between k and $k+1$; a , b , and c represent vehicle consist resistance parameters; and g represents a grade parameter.

19. The method of claim 15 further comprising:

determining a plurality of combined tractive effort parameters of all of the plurality of vehicles based on a plurality of the acquired tractive effort parameters of the command vehicle and based on a plurality of calculated tractive effort parameters of the less than all of the plurality of vehicles; and

calculating a distribution of a weight of the vehicle consist based on the determined plurality of combined tractive effort parameters and based on a plurality of the acquired speed parameters of the vehicle consist.

20. The method of claim 19 wherein the distribution of the weight of the vehicle consist is calculated in accordance with:

$$\min_{\theta} (Y - \theta\Phi) (Y - \theta\Phi)',$$

where:

$\theta\Phi = Y + \eta$; Y represents an output vector $[y_1 \dots y_r]$; Φ represents a regressor vector $[\phi_1 \dots \phi_r]$; η represents an error vector $[\eta_1 \dots \eta_r]$;

$$\eta_k = \hat{\theta}\phi_k - y_k;$$

$$\theta = [\alpha \ w_1^c \alpha \dots w_Q^c \alpha];$$

$$y_k = \frac{v_{k+1}^2 - v_k^2}{\delta t} + d_a^l v_{k+1} + d_c^l v_{k+1}^2 + \bar{g}_{k+1}^l v_{k+1} + \bar{g}_k^l v_k;$$

$$\phi_k = \begin{bmatrix} P_k + P_{k+1} - \bar{a}(v_k + v_{k+1}) - \bar{c}(v_k^3 + v_{k+1}^3) \\ (d_a^l - d_a^c)(v_k + v_{k+1}) + (d_c^l - d_c^c)(v_k^2 + v_{k+1}^2) + (\bar{g}_k^l - g_{1,k}^c)v_k + (\bar{g}_{k+1}^l - g_{1,k+1}^c)v_{k+1} \\ \vdots \end{bmatrix};$$

$$\bar{a} = d_b^l n^l (m + 1) + d_b^c n^c N$$

$$\bar{c} = d_d^l a^l + m d_d^t a^t + \sum_{i=1}^N d_d^c a_i^c;$$

where k and r represent a number of data points; P represents a combined tractive effort parameter; v represents a measured speed of the vehicle consist; n represents a number of axles in a unit; a is a cross-sectional area of a unit; d_a , d_b , d_c , and d_d are constants that depend on the unit; the superscripts l , t , and c represent the command vehicle, the vehicles other than the command vehicle, and a car of the consist,

respectively; w^l and w_i^c denote the weight of a vehicle and the i^{th} car of the consist, respectively; m represents the number of vehicles less than command vehicle; N represents the number of cars of the consist; g represents a grade parameter; and

where $\bar{g}_k^l = \frac{1}{m+1} \sum_{j=1}^{m+1} g_{j,k}^l$ denotes the grade averaged over the plurality of vehicles.

21. The method of claim 20 wherein the distribution of the weight of the vehicle consist is calculated in accordance with the constraints:

$$\left[(m+1) w^l \quad 1 \quad \dots \quad 1 \right] \theta' = 1, \text{ and}$$

$$\begin{aligned} w_i^c &\geq w_e \\ \Rightarrow w_e \alpha - w_i^c \alpha &\leq 0, \quad i = 1 \dots N, \end{aligned}$$

where w_e represents the weight of an empty car of the consist.

22. The method of claim 15 further comprising:

controlling each of the at least one powered vehicle via a first common power control value; and

calculating the tractive effort of less than all of the plurality of vehicles controlled via the first common power control value.

23. The method of claim 22 further comprising:

controlling each of the powered vehicles via a second common power control value, the second common power control value different than the first common power control value; and

calculating the tractive effort of less than all of the plurality of vehicles controlled via the second common power control value.

24. A method comprising:

measuring a plurality of tractive effort values of a first powered vehicle of a vehicle consist moving along a route;

measuring a plurality of speed values of the vehicle consist moving along the route; and

estimating the tractive effort of one or more second powered vehicles of the vehicle consist based on the measured plurality of tractive effort values and the measured plurality of speed values.

25. The method of claim 24 wherein estimating the tractive effort comprises estimating the tractive effort in accordance with:

$$\hat{P}_{k+1}^t = \frac{1}{k+1} \left(\hat{P}_k^t k + \frac{y_{k+1}}{2\alpha} \right),$$

where:

$\hat{P}_{k+1}^t$ represents a current estimate of horsepower of powered vehicles in the consist less the first powered vehicle; $\hat{P}_k^t$ represents a previous best estimate of the horsepower; α represents the inverse of the weight of the vehicle consist; k represents a time point;

$$\begin{aligned} y_k \text{ represents } & \frac{v_{k+1}^2 - v_k^2}{\delta t} + g_{k+1}v_{k+1} + g_kv_k - \left(P_{k+1}^l + P_k^l \right) \alpha \\ & + (v_{k+1} + v_k) a \\ & + \left(v_{k+1}^2 + v_k^2 \right) b \\ & + \left(v_{k+1}^3 + v_k^3 \right) c \end{aligned} ;$$

P_k represents a measured tractive effort parameter of the first powered vehicle; v represents a measured speed of the vehicle consist; δt represents a time difference between k and $k+1$; a , b , and c represent vehicle consist resistance parameters; and g represents a grade parameter.

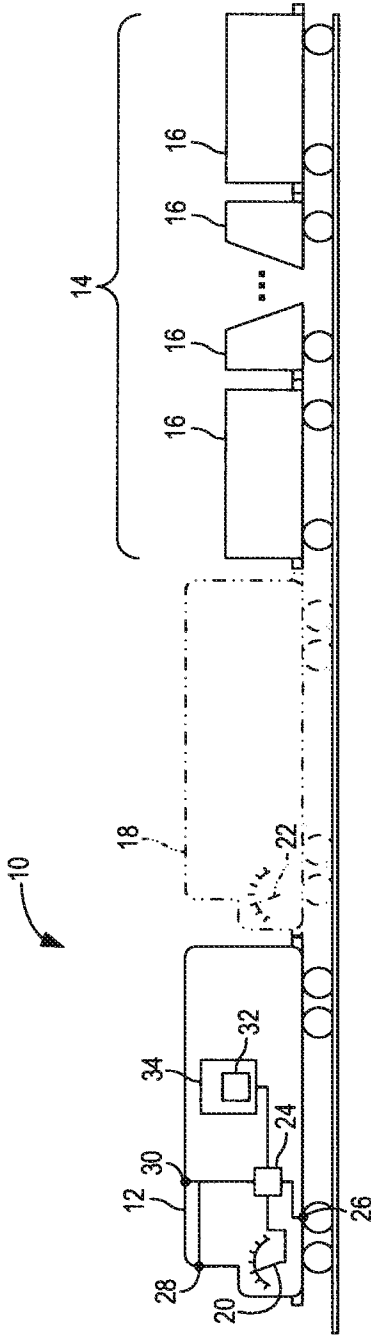


FIG. 1

2/4

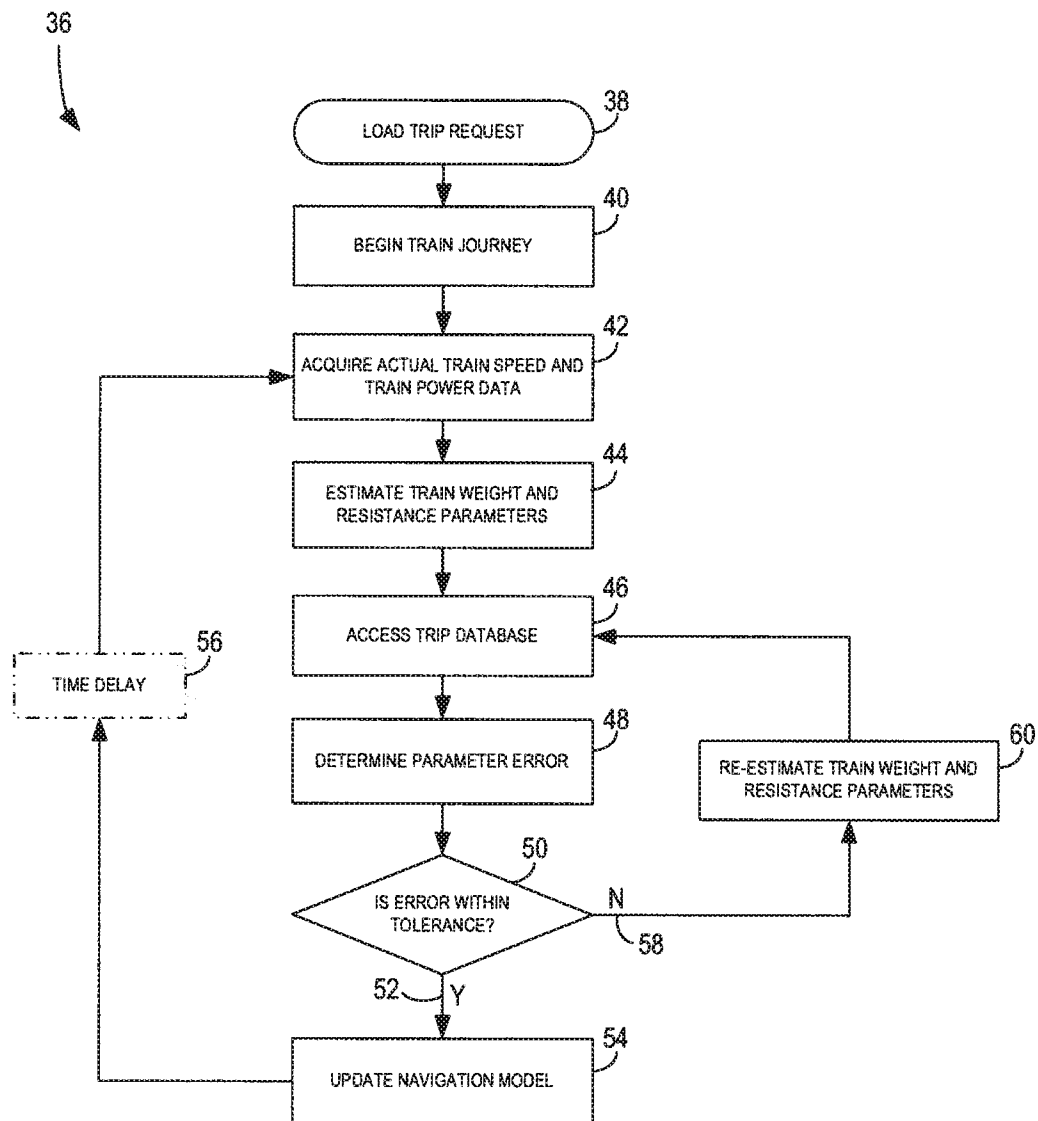


FIG. 2

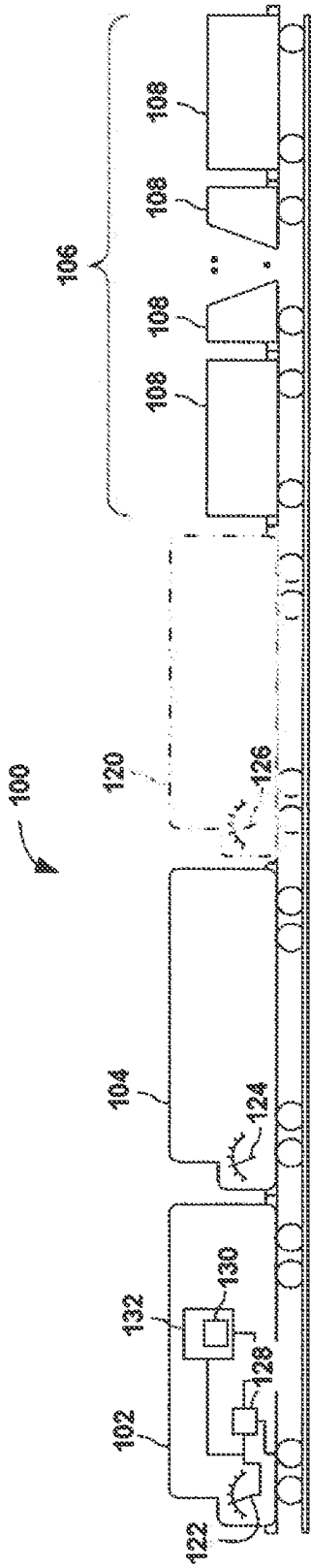


FIG. 3

4/4

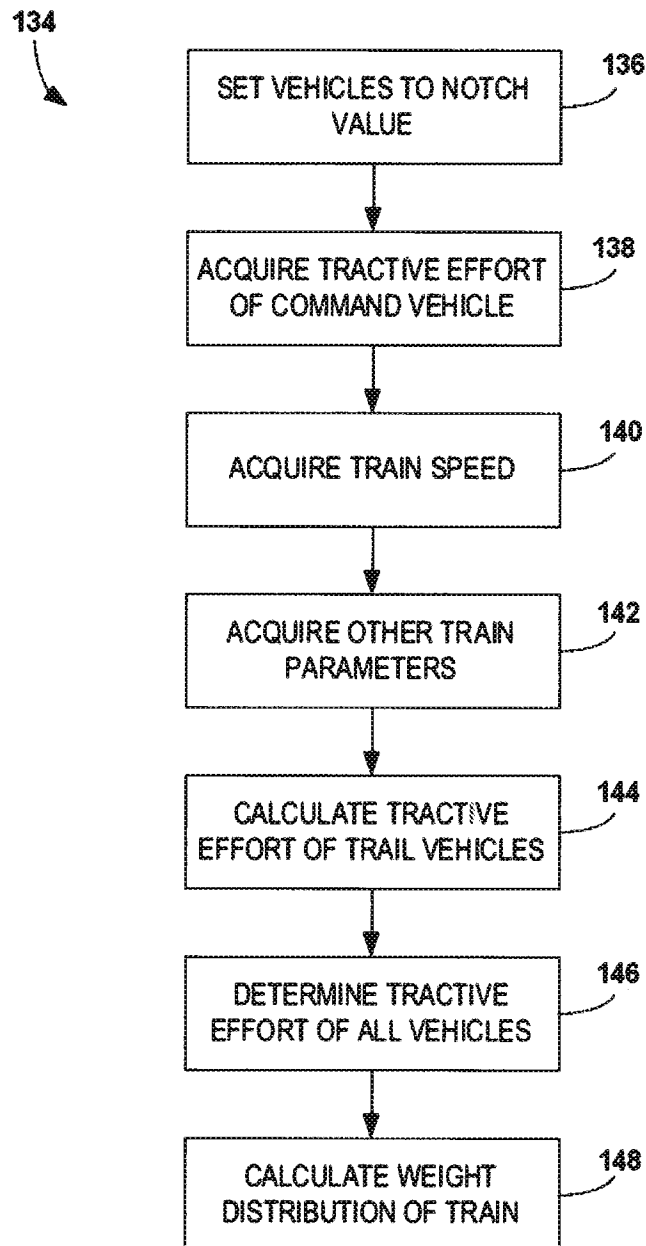


FIG. 4