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(54) **POWER MANAGEMENT OF A HYBRID VEHICLE**

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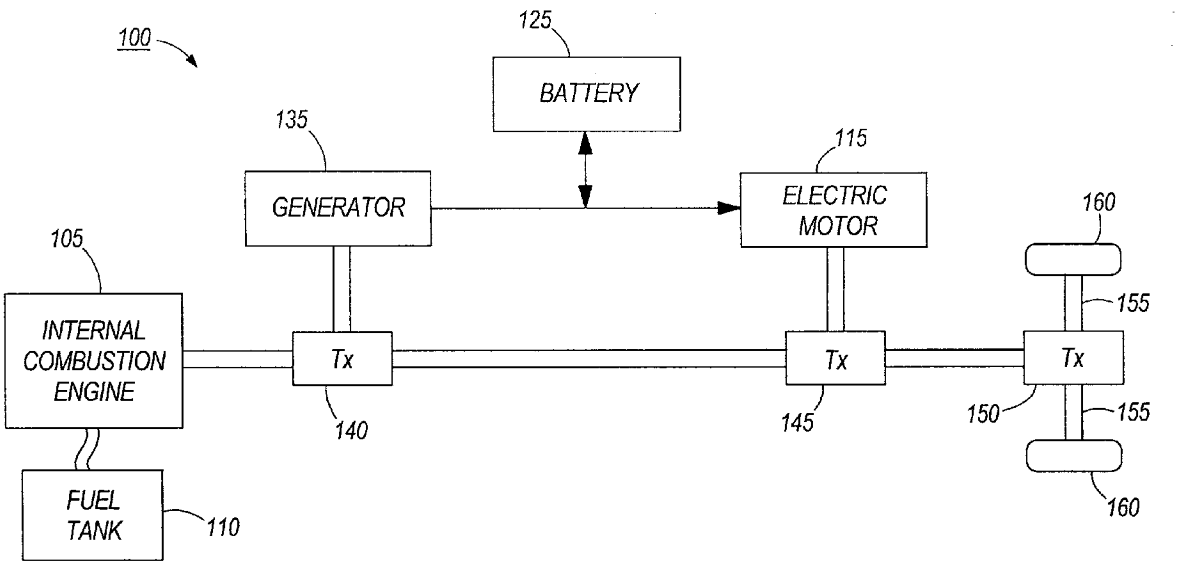
(57) **ABSTRACT**

A system and method of determining and applying power split ratios to power sources within hybrid vehicles. The power split ratio is determined using a two-scale dynamic programming technique to achieve optimal state of charge depletion over the course of a trip. On the macro-scale level, a global state of charge profile is created for the entire trip. On the micro-scale level, the state of charge profile and accompanying power split ratio is recalculated at the end of each segment as the vehicle proceeds along the trip. Various trip modeling techniques are used to provide constraints for the dynamic programming.



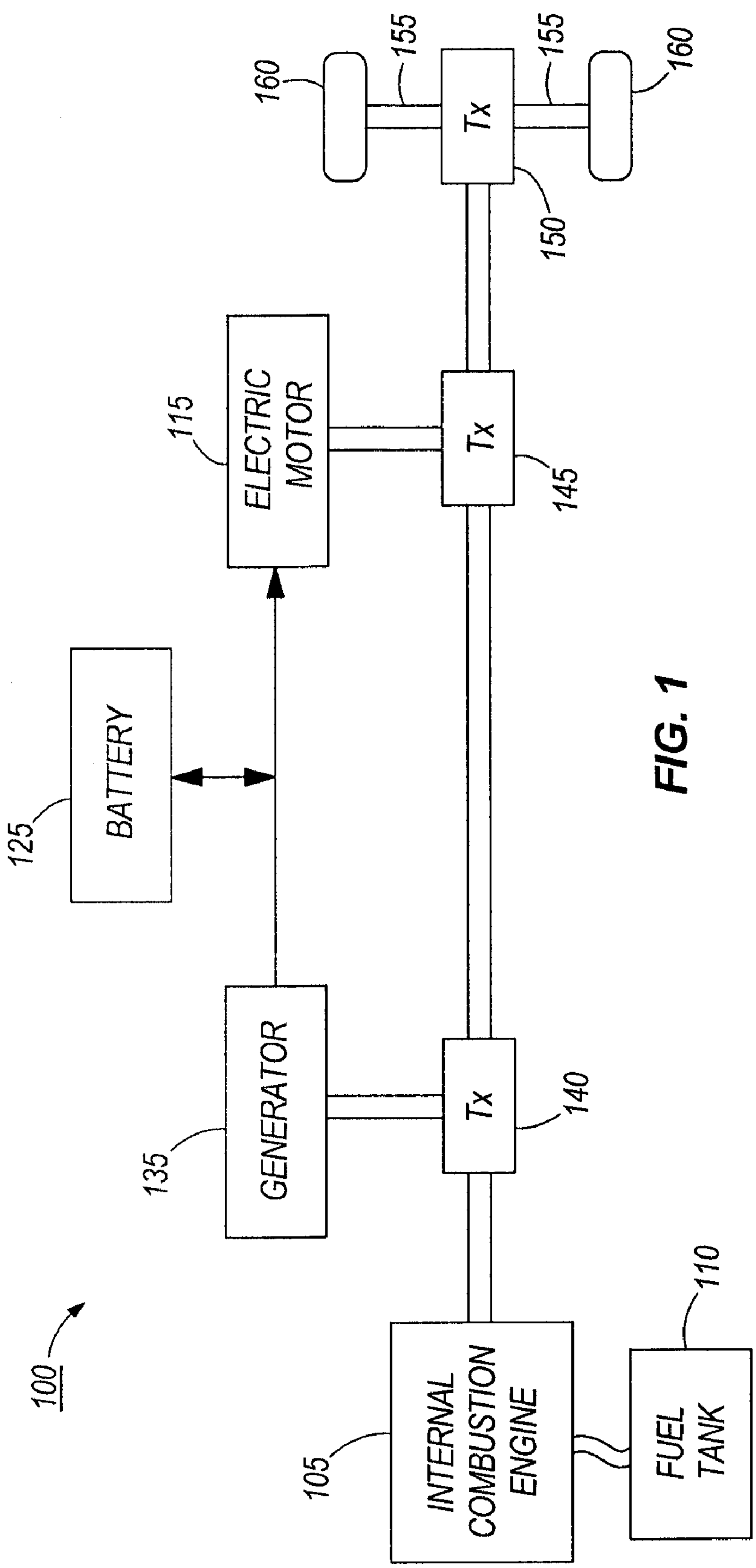

100
INTERNAL COMBUSTION ENGINE
105
FUEL TANK
110
GENERATOR
135
Tx
140
BATTERY
125
ELECTRIC MOTOR
115
Tx
145
Tx
150
155
155
160
160

FIG. 1

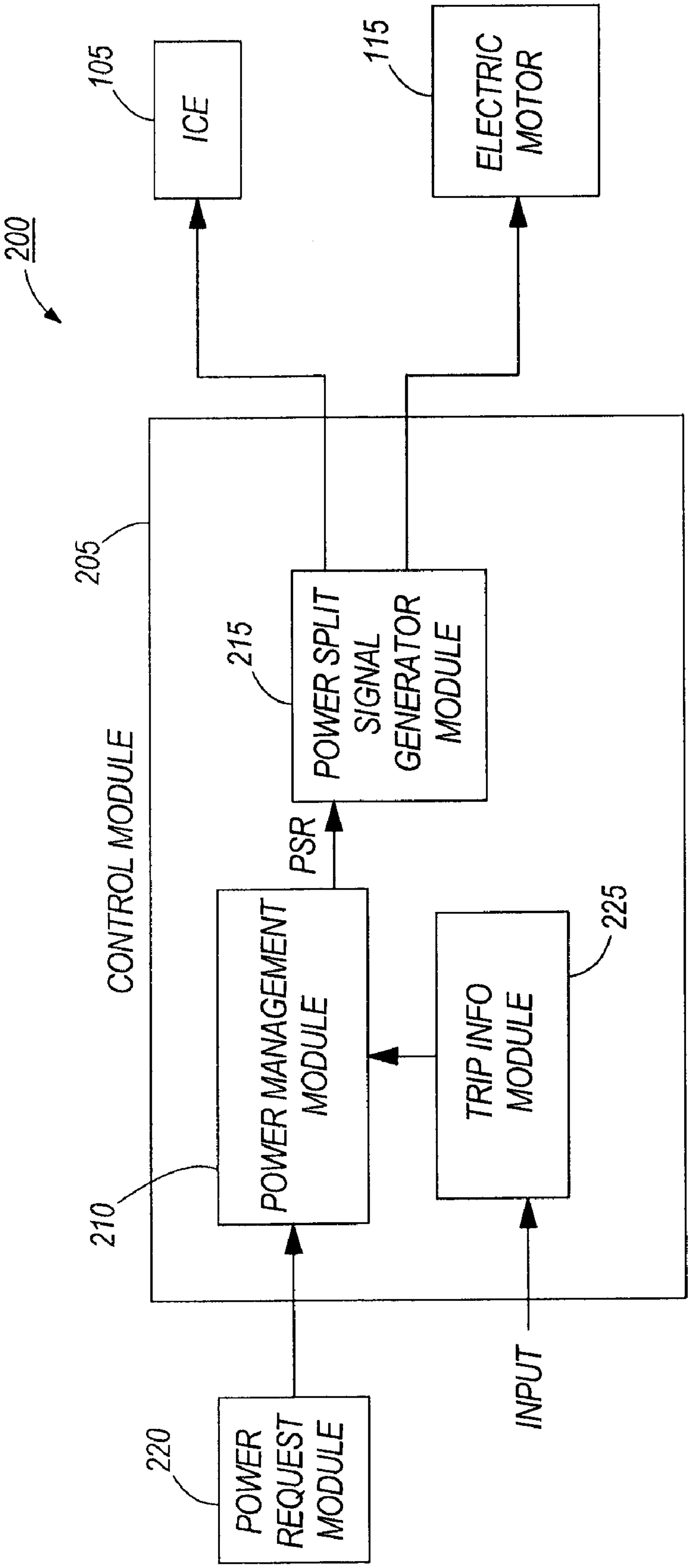

200
105
ICE
115
ELECTRIC MOTOR
205
CONTROL MODULE
215
POWER SPLIT SIGNAL GENERATOR MODULE
PSR
210
POWER MANAGEMENT MODULE
225
TRIP INFO MODULE
220
POWER REQUEST MODULE
INPUT

FIG. 2

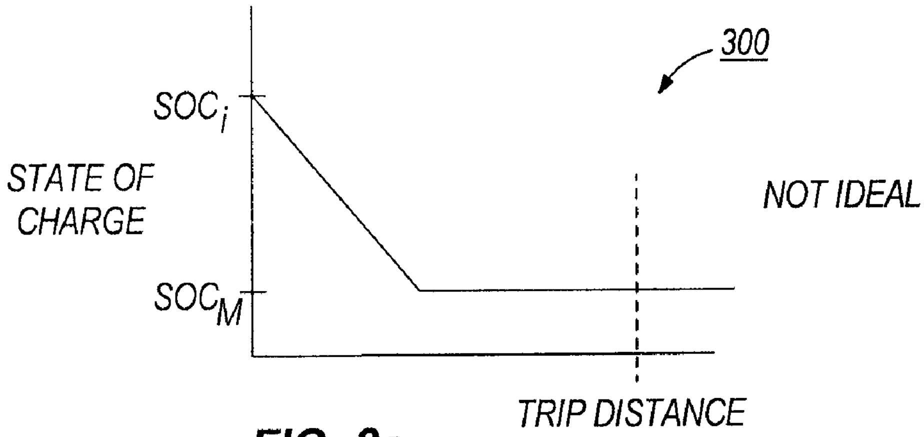


FIG. 3a

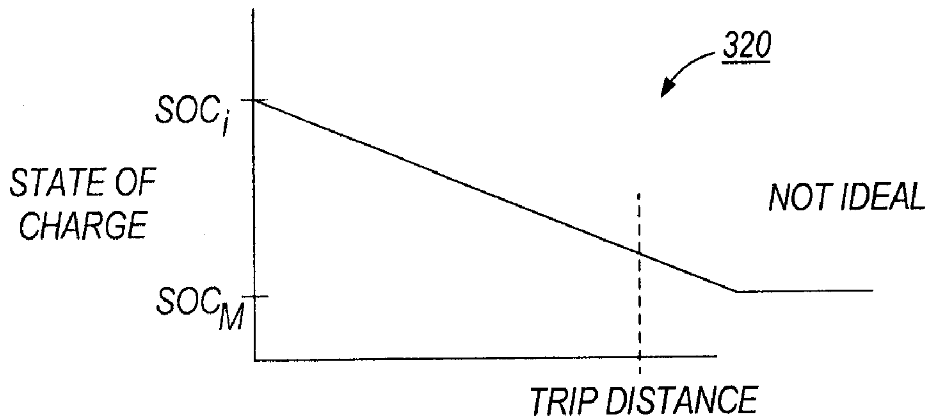


FIG. 3b

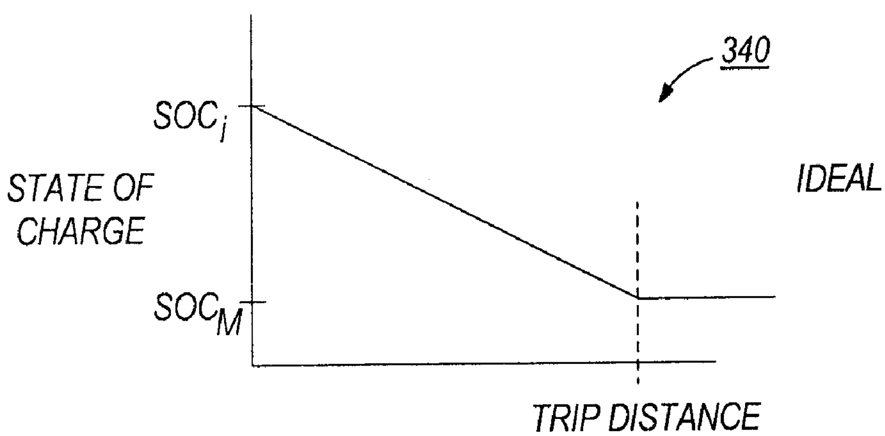


FIG. 3c

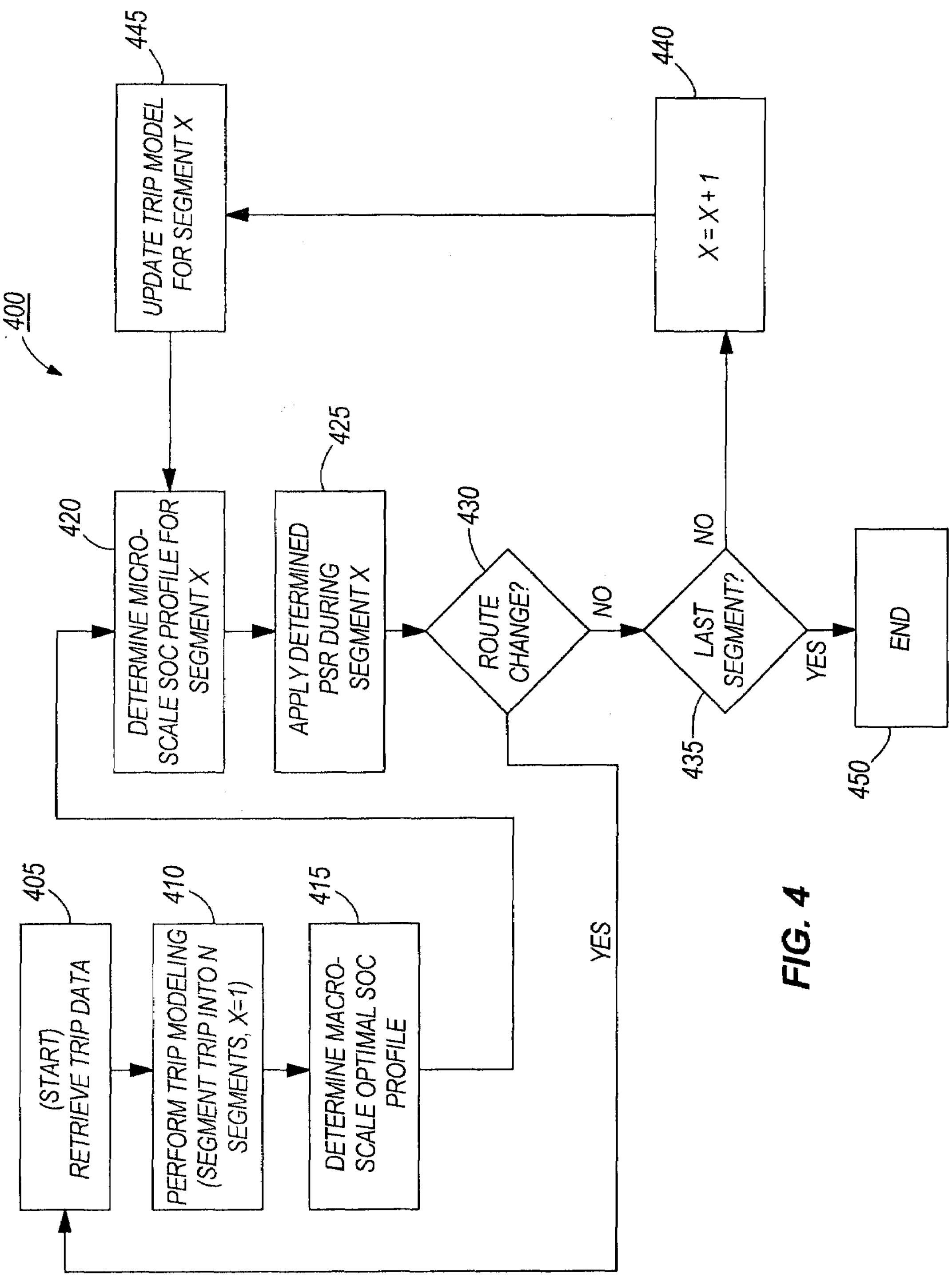

400
(START) RETRIEVE TRIP DATA
405
PERFORM TRIP MODELING (SEGMENT TRIP INTO N SEGMENTS, X=1)
410
DETERMINE MACRO-SCALE OPTIMAL SOC PROFILE
415
DETERMINE MICRO-SCALE SOC PROFILE FOR SEGMENT X
420
APPLY DETERMINED PSR DURING SEGMENT X
425
ROUTE CHANGE?
430
YES
NO
LAST SEGMENT?
435
YES
NO
END
450
X = X + 1
440
UPDATE TRIP MODEL FOR SEGMENT X
445

FIG. 4

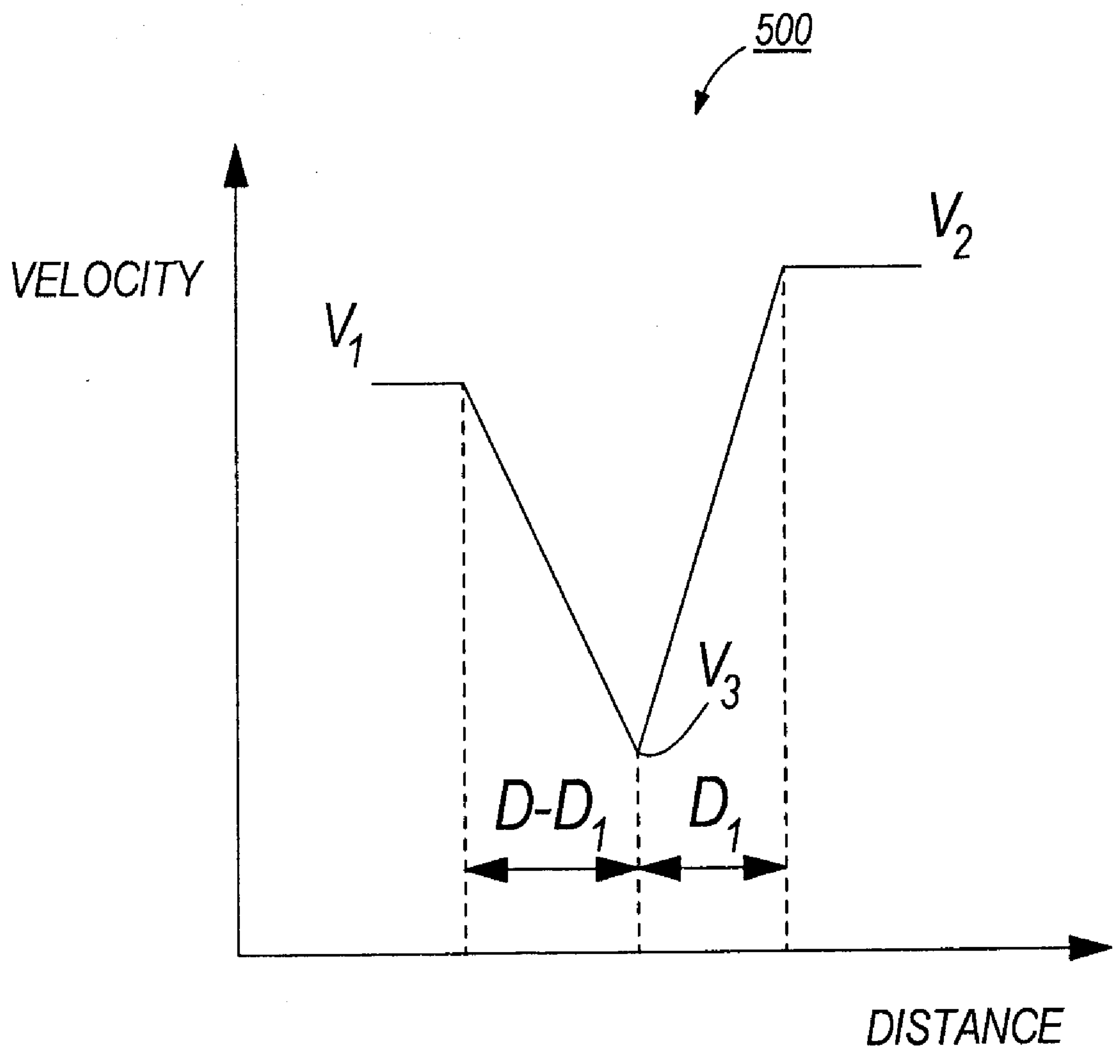
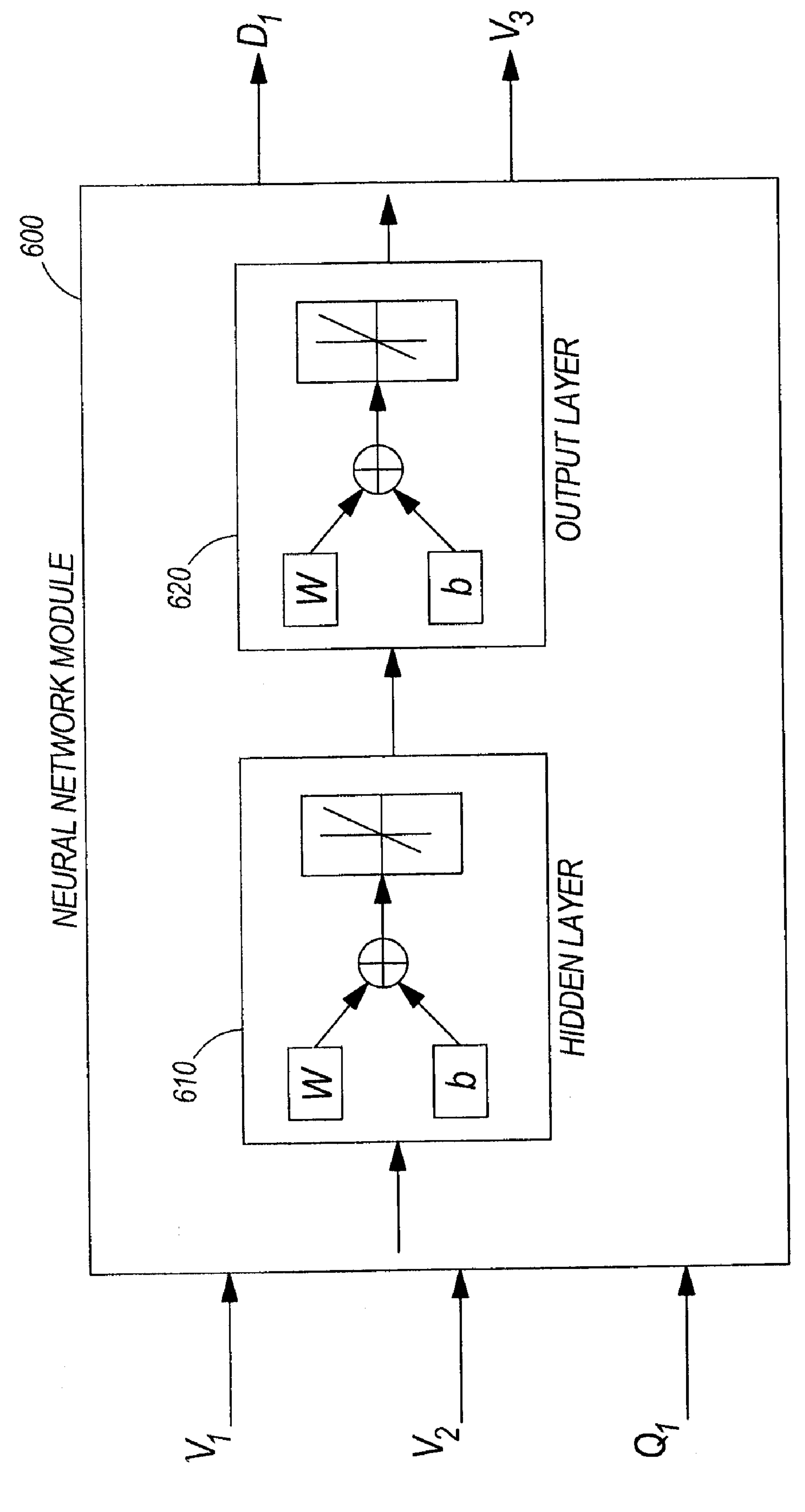


FIG. 5



D_1
V_3
600
NEURAL NETWORK MODULE
620
W
b
OUTPUT LAYER
610
W
b
HIDDEN LAYER
V_1
V_2
Q_1

FIG. 6

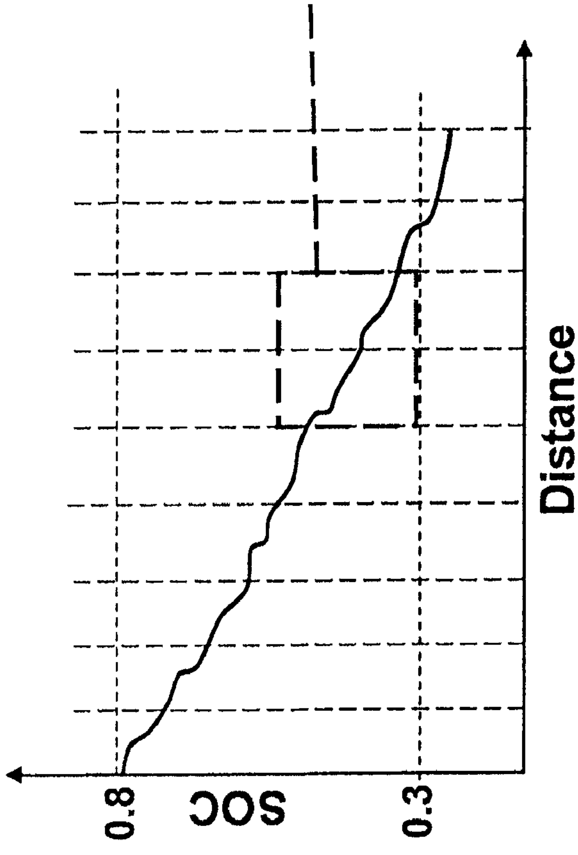

0.8
SOC
0.3
Distance

Fig. 7a

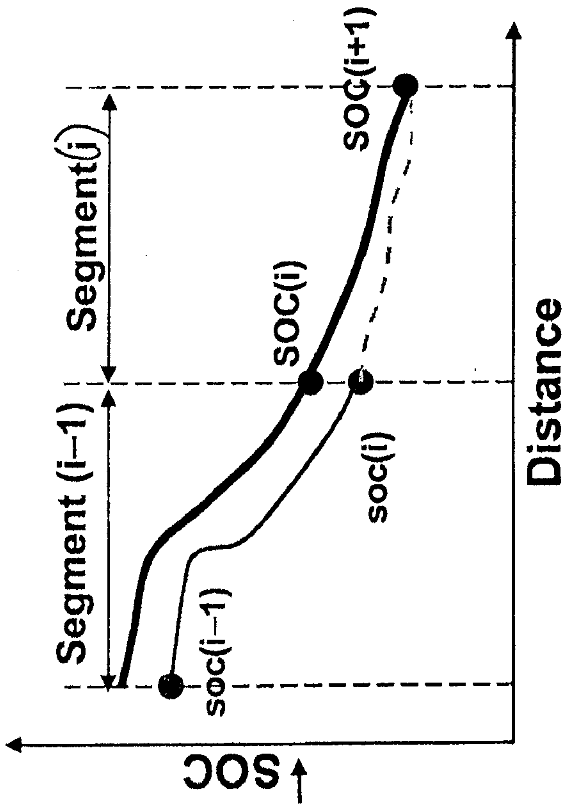

SOC
Segment (i−1)
Segment(i)
SOC(i)
SOC(i+1)
soc(i−1)
soc(i)
Distance

Fig. 7b

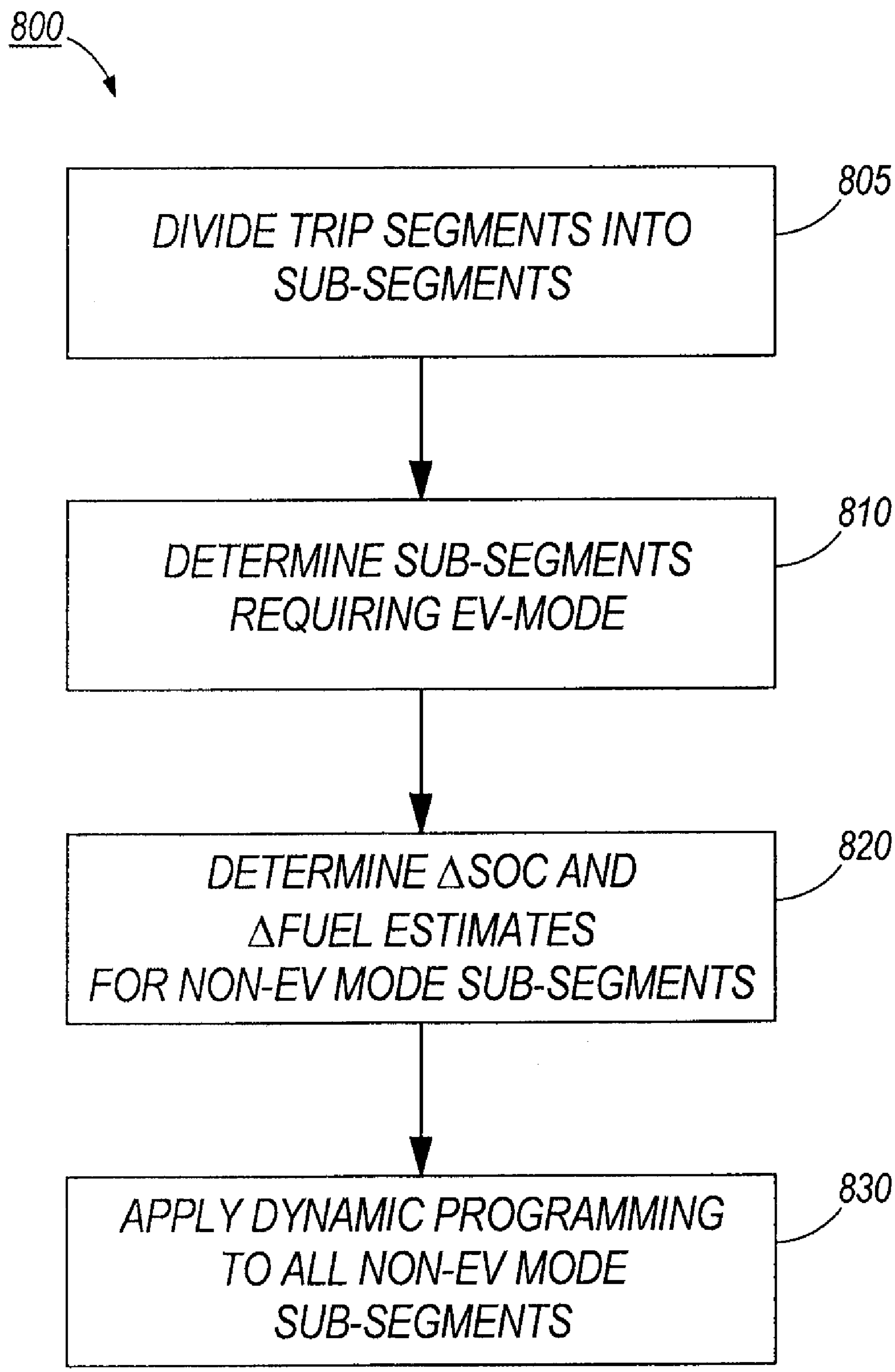

800
DIVIDE TRIP SEGMENTS INTO SUB-SEGMENTS
805
DETERMINE SUB-SEGMENTS REQUIRING EV-MODE
810
DETERMINE ΔSOC AND ΔFUEL ESTIMATES FOR NON-EV MODE SUB-SEGMENTS
820
APPLY DYNAMIC PROGRAMMING TO ALL NON-EV MODE SUB-SEGMENTS
830

FIG. 8

POWER MANAGEMENT OF A HYBRID VEHICLE

RELATED APPLICATIONS

[0001] This application claims priority to provisional application 61/044,983 filed Apr. 15, 2008.

BACKGROUND

[0002] The present invention relates to hybrid vehicles and systems and methods of determining and applying power split ratios to power sources within hybrid vehicles.

SUMMARY

[0003] In one embodiment, the invention provides a hybrid vehicle comprising a drive train, an electric power source coupled to the drive train and including an electric energy storage device having a state of charge, a non-electric power source coupled to the drive-train, and a control system for controlling the transfer of power from the electric power source and the non-electric power source to the drive train. The control system comprises software stored on a computer readable medium for effecting the steps of: establishing a power split ratio between the electric power source and the non-electric power source for a defined trip route so that the state of charge reaches a defined threshold at the end of the trip route, determining the state of charge at various points along the trip route as the vehicle proceeds along the trip route, and recalculating the power split ratio at the various points along the trip route to ensure that the state of charge approximately reaches the defined threshold when the vehicle reaches the end of the trip route.

[0004] In another embodiment the invention provides a method of controlling a hybrid vehicle comprising the steps of retrieving trip data, determining a trip route based on the trip data, dividing the trip route into (n) segments, modeling each of the (n) segments of the trip route to determine a driving cycle along the trip route for the hybrid vehicle, determining a global state of charge profile estimating the state of charge at the end of each of the (n) segments such that the state of charge approximately reaches the defined threshold when the vehicle reaches the end of the trip route, determining a power split ratio for each of the (n) segments based on the actual state of charge at the beginning of a segment about to be traversed and the estimated state of charge at the end of the segment about to be traversed, such that the determined power split ratio causes the state of charge to approximately reach the estimated state of charge at the end of the segment about to be traversed, and applying the determined power split ratio for each of the (n) segments.

[0005] Other aspects of the invention will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. **1** illustrates an exemplary powertrain for a hybrid vehicle according to an embodiment of the invention.

[0007] FIG. **2** illustrates an exemplary control system for a hybrid vehicle according to an embodiment of the invention.

[0008] FIGS. **3***a-c* include graphs depicting the change in a battery's state of charge over the course of a trip for a hybrid vehicle.

[0009] FIG. **4** illustrates an exemplary process for determining and applying a power split ratio according to an embodiment of the invention.

[0010] FIG. **5** illustrates a typical driving cycle for a vehicle on a on/off ramp of a freeway.

[0011] FIG. **6** illustrates an exemplary Neural Network Module according to an embodiment of the invention.

[0012] FIGS. **7***a-b* illustrate estimated and actual state of charge depletion over the course of a trip according to an embodiment of the invention.

[0013] FIG. **8** illustrates an exemplary process for simplified dynamic programming in the spatial domain according to an embodiment of the invention.

DETAILED DESCRIPTION

[0014] Before any embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways.

[0015] As is apparent to those of ordinary skill in the art, the systems shown in the figures are models of what actual systems might be like. Many of the modules and logical structures described are capable of being implemented in software executed by a microprocessor or a similar device or of being implemented in hardware using a variety of components including, for example, application specific integrated circuits ("ASICs"). Terms like "controller" or "module" may include or refer to both hardware and/or software. Furthermore, throughout the specification capitalized terms are used. Such terms are used to conform to common practices and to help correlate the description with the coding examples, equations, and/or drawings. However, no specific meaning is implied or should be inferred simply due to the use of capitalization. Thus, the claims should not be limited to the specific examples or terminology or to any specific hardware or software implementation or combination of software or hardware.

[0016] Hybrid vehicles use more than one type of power source for providing power to the vehicle's drive train. Different types of power sources include, for example, internal combustion engines, electric motors, and hydraulic accumulators. These power sources can be fueled by various types of batteries, fuel cells, petroleum products (e.g., gasoline), biofuels, etc.

[0017] In power-split hybrid vehicles, the power sources work together to directly provide driving power to the drive train. In contrast, series hybrid vehicles have a first source directly providing driving power to the drive train, and a second source providing power to the first source. For power-split hybrid vehicles, the relative amounts of power provided from the multiple power sources to the drive train is referred to as the power split ratio ("PSR"). In a power splitting hybrid vehicle with two power sources, a PSR of 60%, and a total power demand Ptotal, the following equations apply:

$$P_{total}=P_{source\ 1}+P_{source\ 2}$$

$$P_{source\ 1}=60\%\times P_{total}$$

$$P_{source\ 2}=40\%\times P_{total}$$

Determining whether to use PSR (e.g., 60%) or 1-PSR (e.g., 40%) in the $P_{source\ 1}$ equation or the $P_{source\ 2}$ equation is an implementation decision. The selection of a PSR can alter the performance of the vehicle, for instance, the fuel efficiency, torque output, and emission levels.

[0018] FIG. **1** depicts a powertrain **100** of an exemplary power-split hybrid vehicle of the invention. A fuel tank **110** provides fuel for an internal combustion engine ("ICE") **105**. The ICE **105** is coupled to a transmission **140** that enables the ICE **105** to provide mechanical power to a generator **135** and transmission **145**. The generator may provide electrical power to both a battery **125** and an electric motor **115**. The battery is capable of receiving and storing electrical power from the generator **135** to increase its total state of charge ("SOC"). The battery **125** is also capable of outputting electrical power to the electric motor **115**, which decreases the SOC of the battery **125**. The electric motor **115** receives electrical power from the generator **135** and/or the battery **125** and converts it to mechanical power to drive the transmission **145**. Thus, the transmission **145** may receive mechanical driving power from both the ICE **105** and the electric motor **115**. Thereafter, the transmission **145** provides mechanical driving power to the wheels **160** via transmission **150** and axles **155**, which propels the hybrid vehicle. In alternative embodiments, the powertrain provides power to two or more axles. In other embodiments, the powertrain **100** does not include a generator **135** or transmission **140**. Therefore, the battery **125** can not be recharged by the ICE **105**. Instead, the battery **125** is recharged by solar panels, a main power grid (e.g., via a plug-in connection), or other power sources.

[0019] FIG. **2** depicts a control system **200** to be used with a powertrain of a power-split hybrid vehicle, such as powertrain **100**. The control system **200** includes a Control Module **205** with a Power Management Module **210**, Trip Information ("Info") Module **225**, and Power Split Signal Generator Module **215**. The Control Module **205** receives input from the Power Request Module **220**. The Power Request Module **220** can include, for example, an accelerator pedal operated by a driver of the hybrid vehicle. The Power Request Module **220** can convert a mechanical action, such as a depression of the accelerator or brake pedal, into an electronic signal indicating the driver's desired acceleration or deceleration level. The Trip Info Module **225** provides information about the driver's intended and on-going trip. Information received and provided by the Trip Info Module **225** can include destination information, current location information, time of day information, speed information, route information, traffic information, construction information, and a battery's current state of charge ("SOC").

[0020] The Power Management Module **210** receives the information output from the Power Request Module **220** and the Trip Info Module **225**. The Power Management Module **210** uses the information received to calculate a PSR, which is output to the Power Split Signal Generator **215**. The Power Split Signal Generator **215**, in turn, calculates the power request amount for each of the ICE **105** and the electric motor **115**. The ICE **105** power request can be calculated by multiplying the PSR by the total power request (e.g., 40%×total power request=power request for ICE **105**). The electric motor **115** power request can be calculated by multiplying (1-PSR) by the total power request (e.g., 60%×total power request=power request for electric motor **115**. Therefore, calculating and applying a PSR to the ICE **105** and electric motor **115** causes the ICE **105** to provide the same power, more power, or less power than the electric motor **115** to propel the hybrid vehicle. In other embodiments, the Power Split Signal Generator Module **225** multiplies the PSR by the total power request to determine the electric motor **115** power request, and multiplies (1-PSR) by the total power request to determine the ICE **105** power request.

[0021] Graphs **300**, **320**, and **340** of FIGS. **3***a-c* depict SOC values for a power-split hybrid vehicle battery, such as battery **125**, over the course of a trip. The power-split hybrid vehicle for FIGS. **3***a-c* includes generator **135** to maintain the battery level once it reaches it's lowest healthy SOC level (SOC_m). At the beginning of a trip, the initial battery level is at SOC_i. In one embodiment, SOC_m=0.3 and SOC_i=0.8. In FIG. **3***a*, the battery's SOC is reduced to SOC_m before the end of the trip, forcing the hybrid vehicle to rely more on the ICE **105** to power the vehicle and maintain the battery's SOC. In FIG. **3***b*, the battery's SOC is not reduced to an SOC_m level at the end of the trip. Therefore, the hybrid vehicle relied on the ICE **105** more than necessary, using more fuel from fuel tank **105**.

[0022] FIG. **3***c* depicts the ideal SOC usage over the course of a trip, such that the vehicle will have the most efficient fuel usage. In FIG. **3***c*, the SOC reaches its lowest healthy level at the end of the trip. Properly chosen PSR levels in accordance with embodiments of this invention will optimize the battery usage such that the battery reaches the SOC_m level at the end of the trip as shown in FIG. **3***c*.

[0023] FIG. **4** shows a method **400** that implements two-scale dynamic programming to dynamically calculate optimal PSR levels for a trip in order to achieve the ideal SOC_m level at the end of the trip. The method **400** can be used, for example, by the control system **200** of FIG. **2**, and is described with reference thereto. Before starting a trip, a user, such as a driver, passenger, or third party, enters trip data into the Trip Info Module **225** (step **405**). The data can include one or more trip destinations (e.g., through longitude and latitude coordinates, cross streets, an address, etc.) and an estimated departure time (which can be assumed the current time unless otherwise specified).

[0024] Next, the Trip Info Module **225** performs trip modeling to find the driving cycle for the trip given the origin, destination, and estimated departure time of the trip (step **410**). The driving cycle includes, for example, vehicle speed, trip time, and acceleration/deceleration rates at each point along the trip. A path-finding algorithm, such as those available via Geographic Information Systems (GIS), will be used to find a route from the origin to the destination. The path-finding algorithm will determine a route based on some or all of the following: road segment lengths, speed limits, historical and real-time traffic data, road slope, intersection/traffic light distribution, and estimated time of departure.

[0025] In one embodiment, once a route is determined, the trip is segmented into a number (n) of segments. There are different ways to segment the trip. For instance, a new segment can be created at each traffic signal (e.g., stop light and stop sign), at each speed limit change (e.g., from 30 mph to 40 mph), at each turn along the route, at any combination of these, or at equidistant locations along the route. The vehicle speed, segment time, and acceleration/deceleration rates are determined for each segment according to a chosen trip modeling approach. Different trip modeling schemes include a simple model, a Gipps car following model, an actual or historic data model, a gas-kinetic model, and a neural network model.

[0026] In step **415**, the control system **200** calculates a macro-scale optimal SOC profile for the entire trip, an example of which is shown in FIG. **7***a*. In FIG. **7***a*, SOC_i is 0.8 and SOC_m is 0.3. The resulting macro-scale SOC trajectory will include an estimated ending SOC level (SOC(x)) for each of the n segments (see, e.g., SOC(i) and SOC(i+1) in FIG. **7***b*). The SOC(x) level for each segment end will be used as reference points throughout the trip to ensure the SOC decreases approximately at an optimal rate (i.e., like that shown in FIG. **3***c*). Calculating the macro-scale optimal SOC profile will be described in more detail below with respect to FIG. **8**.

[0027] In another embodiment, one or both of steps **410** and **415** are implemented by a computational device that is not onboard the hybrid vehicle. That is, the trip information may be sent from the control system or another device to a computational device that performs the trip modeling (step **410**), calculates a macro-scale optimal SOC profile (step **415**), and then transmits the resulting data to the hybrid vehicle control system **200** wirelessly.

[0028] In step **420**, real-time optimization with a micro-scale dynamic programming ("DP") occurs with respect to the first segment of the trip. The initial SOC value (soc(**0**)) and the predicted SOC value for the end of segment **1** (SOC(**1**)), along with updated route information, will be used to calculate an optimal PSR value for the first segment such that the predicted SOC(**1**) is met as the hybrid vehicle reaches the end of that trip segment. The updated route information can include historical or, preferably, real-time vehicle speed information along the segment in question (in this case, segment **1**). With the updated driving cycle information, a dynamic programming optimization algorithm is executed to calculate the optimal PSR level for that segment. In step **425**, the control system **200** applies the calculated PSR value and the hybrid vehicle travels the first segment of the trip. If (while the hybrid vehicle is traveling) the control system determines that the user has altered the trip destination or the trip route has changed (step **430**), the method restarts at step **405**.

[0029] If the trip destination and trip route have not changed, as the hybrid vehicle nears the end of the first segment, the control system **200** determines whether any additional trip segments remain (step **435**). The control system **200** can determine that the vehicle is nearing the end of a segment based on, for example, a GPS device or other navigation tools. If additional segments remain, the segment value x is increased by one (step **440**). Thereafter, Trip Info Module **225** performs an update of the trip model for the next segment of the trip (segment **2**) in step **445**. Any of the trip modeling schemes described herein may be used for performing the update in step **445**. The control system then implements step **420** for segment **2** using the actual SOC(**1**) value as the initial SOC value and the predicted SOC(**2**) value to determine an optimal PSR value for the second segment. FIG. **7***b* depicts two segments of the trip, the segment (i−1) which has been completed, and the segment (i), which is about to begin. The solid bold SOC(i) line represents the macro-scale optimal SOC profile. The solid bold SOC(i) line represents the actual SOC level during the i−1 segment. The dashed thin SOC(i) line represents the micro scale SOC level over the segment (i) resulting from the dynamic programming of step **420** for segment (i).

[0030] The method repeats the steps **420-440** to continuously update (in other words, recalculate) and apply the PSR value for each segment until no more segments remain (x=n in step **435**) and the trip is complete (step **450**), or the trip destination or trip route has changed (step **430**) and the process restarts.

Trip Modeling

[0031] If historical and real-time traffic flow data are not available for a given road segment, then a simple modeling scheme (such as constant acceleration/deceleration and constant speed (assumed equal to the speed limit)) can be used. Currently, historical and real-time traffic flow data is often not available on local roads.

[0032] In this simple modeling scheme, traffic sign and signal delays can also be considered. Such traffic sign and signal data is available from local transportation agencies (e.g., Geographical Information Systems (GIS)), and can be quickly transmitted to the vehicle control system **200** in real-time or pre-stored in the on-board memories. In some embodiments, the trip model will assume the vehicle will stop at each traffic signal for a set amount of time (e.g., 30 seconds) and each stop sign for a set amount of time (e.g., 3-5 seconds). In other embodiments, the trip modeling can be synchronized with traffic signal sequences also available from local transportation administrations. The synchronization allows a more accurate model, where the vehicle does not stop at each traffic signal. The traffic signal sequence provides the trip model with the timing for green, yellow, and red lights. The trip model can estimate the vehicle stopping distance on each road segment, given the speed limit and estimated deceleration rate, and then determine whether the car will have to stop at any given traffic signal.

[0033] The microscopic Gipps car following model (the "Gipps model") can increase the accuracy of the driving cycle relative to the simple modeling. The Gipps model is well-suited to model local road segments (road portion between traffic signals) of a trip. In particular, the Gipps model describes the process by which drivers follow each other in traffic streams, i.e., the interaction between vehicles in the same lane. The Gipps model assumes the availability of position and speed information for all vehicles on a road segment by way of navigation devices, such as GPS transmitting devices. The Gipps model, for purposes of this discussion, combines the safety distance model of Gipps, an action point model (which considers driver reaction times), and the traffic signal synchronization modeling as described above. In this Gipps model, all the drivers are assumed to have the same reaction time and each vehicle has the same length.

[0034] Using the Gipps model, the following steps are executed to determine the driving cycle along a road segment for the hybrid vehicle, where (n) vehicles are on the road segment:

[0035] 1) When the vehicle enters the road segment, update the vehicle map and traffic signal sequences from a traffic management center (TMC). K=2.

[0036] 2) Predict the trip model of the leading car (vehicle **1**) with the traffic signal synchronization.

[0037] 3) Predict the driving cycle for the following vehicle (vehicle k) using the Gipps car following model. Determine whether the vehicle (k) will stop before the next traffic light. If so, go to step **4**. Otherwise go to step **5**.

[0038] 4) Set vehicle (k) to be the new leading car. Go to step **1**.

[0039] 5) Check if the trip prediction is done for all (n) vehicles (k=n?). If so, go to step **6**. Otherwise, set (k=k+1), go to step **3**.

[0040] 6) After the above steps, all (n) vehicles trip predictions of the current local road segment are finished. End the process for the current road segment.

[0041] Historical traffic data or real-time traffic data offer an alternative to the simple modeling and Gipps modeling schemes. Historical traffic data may include archived information such as average speed on a road at a given date and time. Real-time traffic data may include average speed at the approximate moment of the information request. Historical and real-time traffic data are available for most metropolitan freeways, e.g., via the Intelligent Transportation System (ITS) archives and real-time monitoring systems. In using the historic and real-time traffic modeling, the driving cycle velocity of a given point on the road segment is the average speed retrieved from the historic or real-time data systems. For the road segment between two data points, a straight line increase or decrease in velocity is assumed. That is, the model assumes constant acceleration and deceleration between data points.

[0042] In some embodiments, different trip modeling techniques are used for on and off ramps for freeways to improve the accuracy of the resulting driving cycle for the on and off ramps. In one embodiment, a gas-kinetic trip modeling is implemented along freeway on/off ramps to provide more accurate driving cycles at such junctions.

[0043] In another embodiment, the trip model near on and off ramps uses a Multi-layer Perceptron (MLP) type neural network using field recorded traffic data. The neural network approach is a less complex trip model than the gas-kinetic model. FIG. **5** depicts the typical driving cycle for a vehicle near freeway on and off ramps in graph **500**. The vehicle starts with an approximated speed V_1 (upstream speed), which is reduced to V_3 (valley speed) as the vehicle approaches other vehicles on the on or off ramp due to the mixing of inflow traffic. After passing the mixing portion, the vehicle can accelerate until it reaches V_2 (downstream speed). D is the distance between two main road detectors, and D_1 is the distance between the valley speed location and the downstream main road detector.

[0044] FIG. **6** depicts a diagram for a MLP Neural Network Module **600** for trip modeling on and off ramps. The MLP Neural Network Module **600** has a hidden layer **610** and an output layer **620**. The MLP Neural Network Module also has three inputs (V_1, V_2, and Q_1) and two outputs (D_1 and V_3), where Q_1 is ramp flow. The training data for the neural network can be obtained by combining the freeway portion of the actual speed profile along with the ramp flow data from traffic sensor data (i.e., from an ITS) retrieved from sensors near the on and off ramps. The back-propagation algorithm is then applied to obtain the model parameters. Thereafter, the model is validated.

[0045] In some embodiments, the trip plan modeling uses a combination of these techniques, for example, the above-described simplified approach or application of the Gipps model for local road segments, the historical traffic data or real-time traffic data for freeway/highway segments, and the neural network model for freeway on/off ramps. The simple model, Gipps model, historical traffic model, and real-time traffic model may be used exclusively or in any combination for trip modeling systems in other embodiments of the invention.

Dynamic Programming

[0046] For a given driving cycle (determined by trip modeling), the goal of the control system **200** is to minimize the fuel consumption, while meeting the speed and torque demand for the vehicle operation. Such an optimization process can be performed by dynamic programming with constraints including the dynamic model for vehicle propulsion and the operational limits of individual components.

[0047] In the discrete-time format, the hybrid vehicle model can be expressed as

$$x(k+1)=f[x(k),u(k)]$$

where x(k) is the state vector of the system (e.g., vehicle speed, transmission gear number, and battery SOC) and u(k) is the vector of control variables (e.g., desired output torque from the engine, desired output torque from the motor, and gear shift command to the transmission). The optimization problem is to find the control input u(k) to minimize the following cost function:

$$J=\sum_{k=0}^{N-1} L[x(k),u(k)]=\sum_{k=0}^{N-1}[\text{fuel}(k)]$$

where N is the duration of the driving cycle, L is the instantaneous cost referring to the fuel consumption (engine emissions are not considered in this equation).

[0048] During the optimization process, the following inequality and equality constraints are satisfied to meet the speed and torque demands and to ensure a safe and smooth operation of the engine, battery, and motor:

Motor Speed: $\omega_{m\_min} \leqq \omega_m(k) \leqq \omega_{m\_max}$

Motor Torque: $T_{m\_min}[\omega_m(k),SOC(k)] \leqq T_m(k) \leqq T_{m\_max}[\omega_m(k),SOC(k)]$

ICE Speed: $\omega_{e\_min} \leqq \omega_e(k) \leqq \omega_{e\_max}$

ICE Torque: $T_{e\_min}[\omega_e(k)] \leqq T_e(k) \leqq T_{e\_max}[\omega_e(k)]$

State of Charge: $SOC_{min} \leqq SOC(k) \leqq SOC_{max}$

Vehicle Speed: $v_v(k)=v_{v\_req}(k)$

Torque Demand: $T_m(k)+T_e(k)=T_{req}(k)$

[0049] As mentioned above, this optimization process can be performed by using a dynamic programming (DP) algorithm. The dynamic programming (DP) algorithm is used to determine the macro-scale optimal SOC profile and PSR values. Dynamic Programming (DP) is a general dynamic optimization approach that can provide a globally optimal solution to a constrained nonlinear programming problem. Based on Bellman's Principle of Optimality, the optimal policy can be obtained by solving the sub-problems of optimization backward from the terminal condition.

[0050] The sub-problem for the (N−1) step is to minimize:

$$J_{N-1}^*[x(N-1)] = \min_{u(N-1)} \{L[x(N-1), u(N-1)] + G[x(N)]\}$$

For step k (0<k<N−1), the sub-problem is to minimize:

$$J_k^*[x(k)] = \min_{u(k)}\{L[x(k), u(k)] + J_{k+1}^*[x(k+1)]\}$$

and the cost function to be minimized is defined by:

$$J = \sum_{k=0}^{N-1} L[x(k), u(k)] = \sum_{k=0}^{N-1} [\text{fuel}(k) + \mu \cdot NOx(k) + \nu \cdot PM(k)]$$

[0051] J_k*[x(k+1)] is the optimal cost-to-go function at state x(k) starting from time stage k. The above recursive equation is solved backward to find the control policy. The minimizations are performed subject to the inequality and equality constraints imposed by the driving cycle determined via trip modeling and depicted above.

[0052] An effective way to solve the above cost function numerically is through quantization and interpolation. For continuous state space and control space, the state and control values are first discredited into finite grids. At each step of the optimization search, the function J_k[x(k)] is evaluated only at the grid points of the state variables. If the next state x(k+1) does not fall exactly on a quantized value, then the value of J_k*[x(k+1)] as well as G[x(N)] are determined through linear interpolation. At each step, the backward DP with interpolation method was used. For some cases, the vehicle can be assumed fully charged to the highest healthy level, typically SOC of 0.8, while the healthy low level of SOC is 0.3. In these instances, the DP problem is solved with the initial and terminal values of SOC at 0.8 and 0.3, respectively, as boundary conditions.

[0053] Solving the DP in the time domain, as described above, can be computationally complex and may require computational power in excess of that available in some on-board vehicle control systems **200**. In these instances, the DP can be solved using an outside or off-board system, with the resulting optimal macro-scale SOC profile and PSR levels being transferred wirelessly to the control system **200**.

[0054] In another embodiment, the macro-scale optimal SOC profile can be determined in step **415** in the spatial domain using a simplified DP approach. This simplified DP approach is illustrated in FIG. **8** and is less computationally complex than the time-domain approach. Thus, the simplified DP approach is more easily computed using on-board vehicle systems, such as control system **200**.

[0055] The simplified DP approach used to obtain the macro-scale SOC profile (step **415**) is depicted in FIG. **8**. The control system first divides each segment into sub-segments of approximately the same length (step **805**). The control system then analyzes the driving cycle produced through trip modeling to determine which sub-segments of the trip include significant acceleration or deceleration (step **810**). The vehicle will operate in an electric vehicle (EV) mode for these sub-segments. In the EV mode, the PSR ratio is chosen such that electric motor satisfies 100% of the vehicle's propulsion needs and the ICE provides no power (i.e., PSR=0). The control system **200** will also determine the estimated change in SOC (ΔSOC) for the EV mode sub-segments, (change in fuel (Δfuel) will be zero). A look-up-table (LUT) populated with estimates of ΔSOC based on the driving cycle's acceleration and deceleration estimates of the EV mode segments can be used to estimate ΔSOC.

[0056] In step **820**, the control system **200** analyzes the non-EV mode sub-segments of the trip to determine an estimated ΔSOC and Δfuel for each sub-segment according to each possible value of PSR. In one embodiment, PSR is a value between 0 and 1 in $1/10^{th}$ increments (e.g., 0.0, 0.1, 0.2, . . . 0.9, 1.0). The PSR increments can be smaller or larger in other embodiments. To determine the estimated ΔSOC and Δfuel for each sub-segment, the total power demand (speed× torque) and selected PSR is used to determine the power demand from the ICE and electric motor (for the selected PSR). The fuel rate can be found from a fuel map for the hybrid vehicle based on the average speed and the torque. The Δfuel is equal to the product of the fuel rate and the predicted driving time of the sub-segment. The ΔSOC is equal to the numerical integration for the battery dynamics within the sub-segment driving time. By ignoring the temperature effect and the internal capacitance, a simplified battery model in discrete time is:

$$SOC(k+1)SOC(k) - \frac{V_{oc} - \sqrt{V_{oc}^2 - 4(R_{int} + R_t) \cdot T_m \cdot \omega_m \cdot \eta_m^{-sgn(T_m)}}}{2(R_{int} + R_t) \cdot Q_b}$$

where the internal resistance R_{int} and the open circuit voltage V_{oc} are functions of the battery SOC, Q_b is the maximum battery charge, R_t is the terminal resistance, and $\omega_m * \eta_m^{-sgn(Tm)}$ is the efficiency of the electric motor.

[0057] In another embodiment, a look-up-table is populated with estimated ΔSOC and Δfuel values for different sub-segment driving cycle characteristics. This eliminates the need to perform algebraic calculations in real-time, as described in the preceding paragraph. Instead, the algebraic calculations are performed before a trip occurs and stored in the look-up-table.

[0058] In step **830**, after the sub-segment-wise ΔSOC and Δfuel are calculated for the non-EV mode sub-segments with all possible PSR values, DP is applied to the corresponding spatial domain optimization. DP is applied to the non-EV mode sub-segments of the trip using (ΔSOC_{NET}+ΔSOC_t) as the initial SOC value and ΔSOC_t as the terminal SOC value. SOC_s is the initial SOC value for the trip (e.g., 0.8 if at the typical highest healthy SOC level) and ΔSOC_{NET}=SOC_s−SOC_t+the sum of each ΔSOC for all EV-mode sub-segments.

[0059] Performing DP provides the estimated ΔSOC for each non-EV sub-segment, which can then be combined with the estimated ΔSOC for each EV sub-segment. Thus, a macro-scale SOC profile across the entire trip results, which is divided according to the original (n) segments from the trip model.

[0060] In step **420**, a micro-scale SOC profile is determined for the upcoming segment (x) using DP. The DP can use an updated driving cycle resulting from step **445** that uses real-time traffic data (when available), or updates already-retrieved historic traffic data based on estimated trip times with historical traffic data based on actual/current trip times. Updating (also referred to as recalculating) the driving cycle allows a more accurate DP solution because the driving cycle constraints are more accurate. Using the updated driving cycle, the power split ration is updated (recalculated) in step **425**.

[0061] Also, the micro-scale DP algorithm uses updated SOC constraints to more accurately determine a micro-scale SOC profile and PSR values. During the trip, the actual ΔSOC may differ from that in the macro-scale SOC profile, as the macro-scale SOC profile is merely an estimation. For instance, the driver may brake or accelerate more or less than expected, changing the demand from the battery, and, thus, the battery's SOC at the end of a segment may not be as expected. Therefore, as discussed above with reference to FIG. **7**(*b*), the initial SOC value used is the actual SOC at the end of the current segment (soc(i)). The terminal SOC value used is the estimated SOC level at the end of the next segment (SOC(i+1)).

[0062] Similar to the macro-scale DP algorithm, the micro-scale DP algorithm can be solved either in the time or spatial domain. However, the time domain micro-scale DP is less complex than the macro-scale DP problem; therefore, an on-board control system is more likely to be able to perform the micro-scale DP than the macro-scale DP in the time domain. The spatial domain micro-scale DP is less complex than the micro-scale DP in the time domain.

[0063] In another embodiment, pattern recognition is used to account for driver behavior that is inconsistent with the trip models' driving cycle predictions. For instance, the acceleration/deceleration rates may be higher for a more "sporty" driver (thus shorter time periods for acceleration/deceleration), or lower for a more conservative driver (thus longer time periods for acceleration/deceleration). By better predicting the transition period from an acceleration to approximate constant speed segment and from a constant speed segment to deceleration, better fuel efficiency is achieved. The pattern recognition will be applied, for example, in step **425**, to more accurately transition between the EV mode and the PSR values determined via micro-scale DP for local road segments.

[0064] To determine the time to transition from an acceleration EV-mode to the DP micro-scale-determined PSR value for approximately constant speed, the following criteria is used:

[0065] 1) $a<a_{threshold}$

[0066] 2) $V_{lim}-V_{threshold}<V>V_{lim}+V_{threshold}$

[0067] 3) Transition region: $[S_i+S_1, S_i+S_2]$

Where (a) is the acceleration rate of the vehicle, ($a_{threshold}$) is the threshold value of the transition, (V_{lim}) is the speed limit of the segment, (S_i) is the location of the (i^{-th}) traffic stop, (S_1) is the lower bound of the transition region, and (S_2) is the upper bound of the transition region.

[0068] To determine the time to transition from the DP micro-scale-determined PSR value for approximately constant speed to a deceleration EV-mode to, the following criteria is used:

[0069] 1) $b<b_{threshold}$

[0070] 2) $V_{lim}-V_{threshold}<V<V_{lim}+V_{threshold}$

[0071] 3) Transition region: $[S_{i+1}-S_3, S_{i-1}]$

Where (b) is the deceleration/braking rate of the vehicle, ($b_{threshold}$) is the threshold value of the transition, (V_{lim}) is the speed limit of the segment, (S_{i+1}) is the location of the ($i+1^{-th}$) traffic stop, and (S_3) is the lower bound of the transition region.

[0072] Thus, the invention provides, among other things, systems and methods of determining and applying power split ratios to power sources within hybrid vehicles to improve fuel efficiency and battery usage. Various features and advantages of the invention are set forth in the following claims.

What is claimed is:

1. A hybrid vehicle comprising:

a drive train;

an electric power source coupled to the drive train and including an electric energy storage device having a state of charge;

a non-electric power source coupled to the drive-train; and

a control system for controlling the transfer of power from the electric power source and the non-electric power source to the drive train, the control system comprising software stored on a computer readable medium for effecting the steps of:

establishing a power split ratio between the electric power source and the non-electric power source for a defined trip route so that the state of charge reaches a defined threshold at the end of the trip route;

determining the state of charge at various points along the trip route as the vehicle proceeds along the trip route; and

recalculating the power split ratio at the various points along the trip route to ensure that the state of charge approximately reaches the defined threshold when the vehicle reaches the end of the trip route.

2. The hybrid vehicle of claim **1**, further comprising software stored on the computer readable medium for effecting the steps of:

segmenting the trip route into (n) segments, and

modeling the trip route to create a driving cycle that includes a velocity profile of the hybrid vehicle for the trip route.

3. The hybrid vehicle of claim **2**, wherein the modeling the trip route comprises selecting a trip model to use to model each of the (n) segments, wherein the trip model is one of:

a gas-kinetic trip model,

a Gipps car following model,

a neural network model,

a trip model using historical or real-time traffic data and constant acceleration and deceleration rates, and

a simple trip model using constant acceleration, constant deceleration, and speed limits as velocity rates.

4. The hybrid vehicle of claim **1**, wherein the power split ratio is established using dynamic programming and is recalculated at the various points along the trip route using dynamic programming.

5. The hybrid vehicle of claim **4**, wherein the dynamic programming uses a driving cycle for the trip route created by trip modeling, and wherein the driving cycle for the trip route comprises a velocity profile of the hybrid vehicle.

6. The hybrid vehicle of claim **4**, wherein the dynamic programming is performed in the spatial domain.

7. The hybrid vehicle of claim **1**, further comprising software stored on the computer readable medium for effecting the step of:

recognizing driving patterns at various points along the trip route as the vehicle proceeds along the trip route, and wherein recalculating the power split ratio is performed based on recognized driving patterns.

8. A method of controlling a hybrid vehicle comprising the steps of:

retrieving trip data;

determining a trip route based on the trip data;

dividing the trip route into (n) segments;

modeling each of the (n) segments of the trip route to determine a driving cycle along the trip route for the hybrid vehicle;

determining a global state of charge profile estimating the state of charge at the end of each of the (n) segments such that the state of charge approximately reaches the defined threshold when the vehicle reaches the end of the trip route;

determining a power split ratio for each of the (n) segments based on the actual state of charge at the beginning of a segment about to be traversed and the estimated state of charge at the end of the segment about to be traversed, such that the determined power split ratio causes the state of charge to approximately reach the estimated state of charge at the end of the segment about to be traversed; and

applying the determined power split ratio for each of the (n) segments.

9. The method of controlling a hybrid vehicle of claim **8**, wherein modeling each of the (n) segments of the trip route further comprises selecting a trip model to use to model each of the (n) segments, wherein the trip model is one of:

a gas-kinetic trip model,

a Gipps car following model,

a neural network model,

a trip model using historical or real-time traffic data and constant acceleration and deceleration rates, and

a simple trip model using constant acceleration, constant deceleration, and speed limits as velocity rates.

10. The method of controlling a hybrid vehicle of claim **8**, wherein determining a power split ratio for each of the (n) segments is performed using dynamic programming.

11. The method of controlling a hybrid vehicle of claim **10**, wherein the dynamic programming uses the driving cycle, and wherein the driving cycle comprises a velocity profile of the hybrid vehicle.

12. The method of controlling a hybrid vehicle of claim **10**, wherein the dynamic programming is performed in the spatial domain.

13. The method of controlling a hybrid vehicle of claim **8**, and further comprising: recognizing driving patterns at various points along the trip route as the vehicle proceeds along the trip route, and wherein determining a power split ratio for each of the (n) segments is based on recognized driving patterns.

14. The method of controlling a hybrid vehicle of claim **8**, wherein determining a power split ratio for each of the (n) segments is based on real-time traffic data received from an information database.

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