ONLINE OPTIMAL CONTROL STRATEGY METHODOLOGY FOR POWER-SPLIT HYBRID ELECTRIC BUS BASED ON HISTORICAL DATA

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ABSTRACT-An online optimal control str

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State Control of September 2019; Revised 26 December 2019; Accepted 26 December 2019)
SSTRACT-An online optimal control strategy methodology on the basis of historical data for a power-split hybrid election
SSTRACT-An onli bus (HEB) is proposed in this study. This approach aims to fully utilize the fuel-saving capability of power-split HEB under real operating cycles and provide an effective way for solving the optimal calibration problem in the application promotion. Firstly, a procedure for synthesizing real-world driving cycles based on cluster analysis and Markov chain method is constructed. Subsequently, dynamic programming (DP) control algorithm is performed to explore the fuel economy potential. Moreover, a DP-based rule control strategy with an automated implementation foundation is introduced to achieve online approximate optimal effect. Finally, offline simulation and hardware-in-the-loop test are conducted. Simulation results validate that the proposed online optimal control strategy methodology has similar fuel-saving performance to DP optimal results and good real-time application conditions.

KEY WORDS : Power-split hybrid electric bus, Online optimal control strategy methodology, Driving cycle synthesis, Fuel economy potential, Hardware-in-the-loop (HIL)

NOMENCLATURE

- θ_{t} : feature vector of synthesized cycle

: feature vector of historical data

: state vector

: control variable

: instantaneous cost
- θ_i
- x
- : control vari
: instantaneo
: allowable le
: allowable u \boldsymbol{u}
- : instantaneous co

: allowable lower

: allowable upper

: allowable lower L
- : state vector

: control variable

: instantaneous cost

: allowable lower limit of SOC r SOC_{min} : allowable lower li
 SOC_{max} : allowable upper li
 $P_{bat,min}$: allowable lower li
 $P_{bat,max}$: allowable upper li
- SOC_{max} : allowable upper limit of SOC range, %
- : allowable upper limit of SOC range, %
: allowable lower limit of battery power,
: allowable upper limit of battery power,
: distance between two working points p $P_{\text{bat,min}}$: allowable lower limit of battery power,
 $P_{\text{bat,max}}$: allowable upper limit of battery power,
 $d(p, o)$: distance between two working points p
 $d_k(p)$: kth distance far away from operating po
- $P_{\text{bat,max}}$: allowable upper limit of battery power, kW
 $d(p, o)$: distance between two working points p and
 $d_k(p)$: kth distance far away from operating point
 $N_k(p)$: kth distance neighborhood for point p
-
- $d_{\rm k}$
- $N_k(p)$: kth distance neighborhood for point p
- $d(p, o)$: distance between two working points p and $d_k(p)$: kth distance far away from operating point $N_k(p)$: kth distance neighborhood for point p reach-dist_k(p,o): kth reachable distance between p (*p*,*o*) : distance between two working points *p* and *o* $\int_{k}(p)$: kth distance far away from operating point *p* $\int_{k}(p)$: kth distance neighborhood for point *p* each-dist_k(*p*,*o*) : kth reachable distance bet (*p*) : kth distance far away from operating point *p*

(*p*) : kth distance neighborhood for point *p*
 *ach-dist*_k(*p*,*o*) : kth reachable distance between po

and *p*

: local reachable density (*p*) : kth distance neighborhood for point *p*

ach-dist_k(*p*,*o*) : kth reachable distance betw

and *p*

: local reachable density
 $\mu_p(p)$: inverse kth distance neighborhood for reach-dist $_{\rm k}$ (*p*,*o*) : kth reachable distance between points *o*
d *p*
cal reachable density
verse kth distance neighborhood for point *p*
ion of set $N_k(p)$ and set $N_{kk}(p)$
- Lrd
-

 $NN_k(p)$: union of set $N_k(p)$ and set $N_{kk}(p)$

and p
local
invers
union
 $)$: nev $N_{kk}(p)$: inverse kth distance ne
 $NN_k(p)$: union of set $N_k(p)$ and
 $NLOF(p)$: new density-based 1
 p (*p*) : inverse kth distance neighborhood for point *p*
 $V_k(p)$: union of set $N_k(p)$ and set $N_{kk}(p)$
 $OF(p)$: new density-based local outlier factor for p
 p (*p*): union of set $N_k(p)$ and set $N_{kk}(p)$
 $DF(p)$: new density-based local outlie
 p

NTRODUCTION *NLOF(p)* : new density-based local outlier factor for point p
1. INTRODUCTION p

1. INTRODUCTION

environmental pollution, hybrid technology has become an
important branch of automotive technology and industrial
innovation (Awadallah *et al.*, 2017; Gavgani *et al.*, 2016). important branch of automotive technology and industrial
innovation (Awadallah *et al.*, 2017; Gavgani *et al.*, 2016).
*Corresponding author: e-mail: wang_yue16@mails.jlu.edu.c innovation (Awadallah *et al.*, 2017; Gavgani *et al.*, 2016).
*Corresponding author: e-mail: wang_yue16@mails.jlu.edu.c hence, the development of hybrid buses is of great
importance for improving energy consumption and urban
environment. With the potential for achieving high fuel
economy, power-split hybrid electric vehicles (HEVs) have importance for improving energy consumption and urban
environment. With the potential for achieving high fuel
economy, power-split hybrid electric vehicles (HEVs) have
been seen as a hybrid powertrain architecture to impro environment. With the potential for achieving high fuel
economy, power-split hybrid electric vehicles (HEVs) have
been seen as a hybrid powertrain architecture to improve
fuel economy (Zeng *et al.*, 2016; Wang *et al.*, economy, power-split hybrid electric vehicles (HEVs) have
been seen as a hybrid powertrain architecture to improve
fuel economy (Zeng *et al.*, 2016; Wang *et al.*, 2014; Qi et
al., 2018). The application of power-split been seen as a hybrid powertrain architecture to improve
fuel economy (Zeng *et al.*, 2016; Wang *et al.*, 2014; Qi et
al., 2018). The application of power-split systems to public
transport of urban areas has become an fuel economy (Zeng *et al.*, 2016; Wang *et al.*, 2014; Qi et *al.*, 2018). The application of power-split systems to public transport of urban areas has become an important trend in the automotive industry. With the decli al.response to provide provide provided in the application of urban areas has become an important trend in automotive industry. With the decline of policy bisidies, power-split systems have become an important oduct layout fo the automotive industry. With the decline of policy
the automotive industry. With the decline of policy
subsidies, power-split systems have become an important
product layout for automotive companies to achieve
strategic t subsidies, power-split systems have become an important
product layout for automotive companies to achieve
strategic transformation.
The fuel economy of power-split systems is highly product layout for automotive companies to achieve
strategic transformation.
The fuel economy of power-split systems is highly
correlated with driving cycles. Thus far, certification

productions are the strategic transformation.

The fuel economy of power-split systems is highly

correlated with driving cycles. Thus far, certification

driving cycles are primary choices for vehicle design The fuel economy correlated with driving
driving cycles are prin
because of their use b The function with driving cycles. Thus far, certification
ving cycles are primary choices for vehicle design
cause of their use by legislative authorities for fuel
onomy and emission certification (Chen *et al.*, 2017; driving cycles are primary choices for vehicle design
because of their use by legislative authorities for fuel
economy and emission certification (Chen *et al.*, 2017;
Borthakur and Subramanian, 2018; Mangun *et al.*, 2017 because of their use by legislative authorities for fuel
economy and emission certification (Chen *et al.*, 2017;
Borthakur and Subramanian, 2018; Mangun *et al.*, 2017;
Fu *et al.*, 2017; Gujarathi *et al.*, 2017). Howev economy and emission certification (Chen *et al.*, 2017; Borthakur and Subramanian, 2018; Mangun *et al.*, 2017; Fu *et al.*, 2017; Gujarathi *et al.*, 2017). However, vehicle operating conditions have discrepancies in dif Fu *et al.*, 2017; Gujarathi *et al.*, 2017). However, vehicle operating conditions have discrepancies in different regions, road characteristics, time, and even climatic conditions. The paper of Shahidineiad *et al.* (20 Fu *et al.*, 2017; Gujarathi *et al.*, 2017). However, vehicle operating conditions have discrepancies in different regions, road characteristics, time, and even climatic conditions. The paper of Shahidinejad *et al.* (201 regions, road characteristics, time, and even climatic
conditions. The paper of Shahidinejad *et al.* (2010) stated
that many problems exist in driving cycles, such as the
underestimation of cruise, acceleration, and stopconditions. The paper of Shahidinejad *et al.* (2010) stated that many problems exist in driving cycles, such as the underestimation of cruise, acceleration, and stop-and-go activities in different velocity brackets. They underestimation of cruise, acceleration, and stop-and-go
activities in different velocity brackets. They concluded
that the real-world power demands of vehicles are difficult
to completely emulate by existing certification activities in different velocity brackets. They concluded that the real-world power demands of vehicles are difficult
to completely emulate by existing certification cycles. At
present, calibration engineers usually need to perform a
large number of calibration work, which greatl that the real-world power demands to completely emulate by existing certification cycles. At present, calibration engineers usually need to perform a large number of calibration work, which greatly increases to completely emiliate by emiliating certification by existence
present, calibration engineers usually need to perform a
large number of calibration work, which greatly increases large number of calibration work, which greatly increases

^{*}Corresponding author. e-mail: wang yue16@mails.jlu.edu.cn *Corresponding author. e-mail: wang_yue16@mails.jlu.edu.cn large number of calibration work, which greatly increases

specific driving cycle. In addition, the calibration effect
depends on the experience of calibration engineers,
wherein consistency and optimality of calibration results
are often difficult to ensure (Duan *et al.*, 2017) depends on the experience of calibration engineers,
wherein consistency and optimality of calibration results
are often difficult to ensure (Duan *et al.*, 2017).
Present hybrid electric buses (HEBs) usually have wherein consistency and optimality of calibration results
are often difficult to ensure (Duan *et al.*, 2017).
Present hybrid electric buses (HEBs) usually have
remote data monitoring equipment that can collect critical

are often difficult to ensure (Duan *et al.*, 2017).
Present hybrid electric buses (HEBs) usually have
remote data monitoring equipment that can collect critical
operation data from vehicles. Effective use of historical are often difficult to ensure (Duan *et al.*, 2017).
Present hybrid electric buses (HEBs) usua
remote data monitoring equipment that can colle
operation data from vehicles. Effective use of
operation data can provide guida Present hybrid electric electric control of the model of the model of the electric elec system optimization; it is also an important exploration for the use of big data. Therefore, exploring a new driving operation data can provide guidance and assistance for system optimization; it is also an important exploration for the use of big data. Therefore, exploring a new driving cycle synthesis method to characterize the vehicle system optimization; it is also an important exploration for
the use of big data. Therefore, exploring a new driving
cycle synthesis method to characterize the vehicle
operating operation is an important basis to ensure th system optimization; it is also an important exploring a new driving
cycle synthesis method to characterize the vehicle
operating operation is an important basis to ensure that an
optimal control strategy can be applied to the use of the vehicle
operating operation is an important basis to ensure that an
optimal control strategy can be applied to specific
application scenarios. The method will effe operating operation is an important basis to ensure that an optimal control strategy can be applied to specific application scenarios. The method will effectively reduce the large calibration workload of current power-spli optimal control strategy can be applied to specific
application scenarios. The method will effectively reduce
the large calibration workload of current power-split buses
and improve the fuel economy under real operating cy application scenarios. The method will effectively reduce
the large calibration workload of current power-split buses
and improve the fuel economy under real operating cycles.
Huertas *et al.* (2018) developed a methodolog the large calibration workload of current power-split buses
and improve the fuel economy under real operating cycles.
Huertas *et al.* (2018) developed a methodology to obtain
representative driving cycles based on simult and improve the fuel economy under real operating cycles.
Huertas *et al.* (2018) developed a methodology to obtain
representative driving cycles based on simultaneous data of
speed, altitude, fuel consumption and tail pip Huertas *et al.* (2018) developed a methodology to obtain representative driving cycles based on simultaneous data of speed, altitude, fuel consumption and tail pipe emissions.
Zhao *et al.* (2018) created the comprehensiv speed, altitude, fuel consumption and tail pipe emissions.
Zhao *et al.* (2018) created the comprehensive principal
component score to cluster micro-trips into homogeneous
groups of observations; this method has good robus Zhao *et al.* (2018) created the comprehensive principal component score to cluster micro-trips into homogeneous groups of observations; this method has good robustness. Peng *et al.* (2019) applied principal component an Zhao *et al.* (2018) created the comprehensive principal
component score to cluster micro-trips into homogeneous
groups of observations; this method has good robustness.
Peng *et al.* (2019) applied principal component ana groups of observations; this method has good robustness.
Peng *et al.* (2019) applied principal component analysis
and K-means clustering method to establish a
representative driving cycle for public urban buses in Peng *et al.* (2019) applied principal component analysis

and K-means clustering method to establish a

representative driving cycle for public urban buses in

Fuzhou City. Lee *et al.* (2011) synthesized representative
 representative driving cycle for public urban buses in Fuzhou City. Lee *et al.* (2011) synthesized representative naturalistic cycles through a stochastic process utilizing transition probability matrices extracted from Fuzhou City. Lee *et al.* (2011) synthesized representative naturalistic cycles through a stochastic process utilizing transition probability matrices extracted from naturalistic driving data collected in the Midwest regio States.
The power-split system includes multiple power sources The probability matrices extracted from and anti-
driving data collected in the Midwest region of the United
States.
The power-split system includes multiple power sources
with complex nonlinear efficiency characteristics.

States.
The power-split system includes multiple power sources
with complex nonlinear efficiency characteristics. The
fuel-saving effects in different application scenarios are The
with
fuel-sa
depend th complex nonlinear efficiency characteristics. The
el-saving effects in different application scenarios are
pendent on control strategies. At present, the dynamic
ogramming (DP) algorithm has been demonstrated fuel-saving effects in different application scenarios are
dependent on control strategies. At present, the dynamic
programming (DP) algorithm has been demonstrated
effective in finding the best fuel economy over certain
 dependent on control strategies. At present, the dynamic 2014; Xi et al., 2018). However, given that realizing DP effective in finding the best fuel economy over certain drive cycles (Xi *et al.*, 2016; Dong *et al.*, 2014; Yang *et al.*, 2014; Xi *et al.*, 2018). However, given that realizing DP algorithm in practice is difficult, r drive cycles (Xi *et al.*, 2016; Dong *et al.*, 2014; Yang *et al.*, 2014; Xi *et al.*, 2018). However, given that realizing DP algorithm in practice is difficult, rule-based control based on DP algorithm has been widely u 2014; Xi *et al.*, 2018). However, given that realizing DP algorithm in practice is difficult, rule-based control based on DP algorithm has been widely used. Kum *et al.* (2011) adopted a comprehensive rule extraction meth on DP algorithm has been widely used. Kum *et al.* (2011) adopted a comprehensive rule extraction method to extract the mode switching rules. shift rules, and optimized power on DP algorithm has been widely used. Kum *et al.* (2011) adopted a comprehensive rule extraction method to extract
the mode switching rules, shift rules, and optimized power
split ratio by observing the DP results of a pl the mode switching rules, shift rules, and optimized power
split ratio by observing the DP results of a plug-in hybrid
system. Zhang *et al.* (2014) applied rule-based control as
an implementable controller with DP results split ratio by observing the DP results of a plug-in hybrid
system. Zhang *et al.* (2014) applied rule-based control as
an implementable controller with DP results on the basis of
the position and battery SOC. Peng *et al* system. Zhang *et al.* (2014) applied rule-based control as an implementable controller with DP results on the basis of the position and battery SOC. Peng *et al.* (2016) proposed a recalibration method to improve the per an implementable controller with DP results on the basis of the position and battery SOC. Peng *et al.* (2016) proposed a recalibration method to improve the performance of a rule-based control strategy through the result the position and battery SOC. Peng $et al.$ (2016) proposed a the position and battery SOC. Peng *et al.* (2016) proposed a recalibration method to improve the performance of a rule-
based control strategy through the results calculated by DP
algorithm. Biasini *et al.* (2013) utili recall the mean-optimal rules were extracted and tuned to design algorithm. Biasini *et al.* (2013) utilized DP algorithm to minimize fuel consumption over a given driving mission.
The near-optimal rules were extracted and tuned to design a rule-based strategy for charge-sustaining ope The near-optimal rules were extracted and tuned to design
a rule-based strategy for charge-sustaining operation
through the analysis of DP control actions.
However, current rule extraction methods are often an a rule-based strategy for charge-sustaining operation through the analysis of DP control actions.

a rule and analysis of DP control actions.
However, current rule extraction methods are often an
observation-based feedback correction process and rely on However, current rule extraction method
observation-based feedback correction proce observation-based feedback correction process and rely on observation-based feedback correction process and rely on

the experiment of vehicle parameters and component
performance parameters may cause changes in global
optimization results. Thus, ensuring universal adaptability
in various driving cycles is difficult, that is, the method performance parameters may cause changes in global
optimization results. Thus, ensuring universal adaptability
in various driving cycles is difficult, that is, the method
does not have the basis for automated implementatio performization results. Thus, ensuring universal adaptability
in various driving cycles is difficult, that is, the method
does not have the basis for automated implementation. To
solve these limitations, an automatic contr in various driving cycles is difficult, that is, the method does not have the basis for automated implementation. To solve these limitations, an automatic control rule extraction method should be developed. Such a method c in various driving cycles in automated implementation. To
does not have the basis for automatic control rule extraction
method should be developed. Such a method can improve
the robustness of online optimal control strateg solve these limitations, an automatic control rule extraction
method should be developed. Such a method can improve
the robustness of online optimal control strategy to driving
cycles, effectively reduce calibration time, method should be developed. Such a method can improve
the robustness of online optimal control strategy to driving
cycles, effectively reduce calibration time, and ensure the
consistency of optimal effects. the robustness of online optimal control strategy to driving
cycles, effectively reduce calibration time, and ensure the
consistency of optimal effects.
This study attempts to explore a methodology to develop the robustness of optimal control and ensure the
consistency of optimal effects.
This study attempts to explore a methodology to develop
an online optimal control strategy with good application

cycles, effectively reduce calibration time, and ensure the consistency of optimal effects.
This study attempts to explore a methodology to develop an online optimal control strategy with good application conditions and au This study attempts to explore
an online optimal control strate conditions and automatic
through the exploration c online optimal control strategy with good application
mditions and automatic implementation capability
ough the exploration of historical data. This
ethodology ensures that the system can maximize the conditions and automatic implementation capability
through the exploration of historical data. This
methodology ensures that the system can maximize the
fuel saving capability under different driving cycles and conditions the exploration of historical data. This
methodology ensures that the system can maximize the
fuel saving capability under different driving cycles and
that the huge calibration workload. First, typical driving methodology ensures that the system can maximize the fuel saving capability under different driving cycles and that the huge calibration workload. First, typical driving cycles are synthesized based on historical operation fuel saving capability under different driving cycles and
that the huge calibration workload. First, typical driving
cycles are synthesized based on historical operation data.
The synthesized driving cycle satisfies the pr that the huge calibration workload. First, typical driving cycles are synthesized based on historical operation data.
The synthesized driving cycle satisfies the probability distribution characteristics of the real operati The huge calculated based on historical operation data.
The synthesized driving cycle satisfies the probability
distribution characteristics of the real operation condition.
Thus, the control robustness of the optimal cont Free synthesized driving cycle satisfies the probability
distribution characteristics of the real operation condition.
Thus, the control robustness of the optimal control strategy
under specific operating conditions can be The symmetrical driving cycle and operation condition.
Thus, the control robustness of the optimal control strategy
under specific operating conditions can be guaranteed.
Subsequently, a global optimization solution is per Thus, the control robustness of the optimal control strategy
under specific operating conditions can be guaranteed.
Subsequently, a global optimization solution is performed
based on the synthesized cycle, and a novel cont under specific operating conditions can be guaranteed.
Subsequently, a global optimization solution is performed
based on the synthesized cycle, and a novel control rule
extraction method to achieve optimal effect similar Subsequently, a global optimization solution is performed. Subsequently, a global optimization is provided as a novel control rule
extraction method to achieve optimal effect similar to DP
algorithm is proposed. In comparison with the existing
methods, the new rule extraction meth extraction method to achieve optimal effect similar to DP algorithm is proposed. In comparison with the existing methods, the new rule extraction method has a general application form, which is more helpful for engineers t algorithm is proposed. In comparison with the existing
methods, the new rule extraction method has a general
application form, which is more helpful for engineers to
understand and apply the control rules. Finally, the methods, the new rule extraction method has a general
application form, which is more helpful for engineers to
understand and apply the control rules. Finally, the
proposed online optimal control strategy is tested and application form, which is more helpful for engineers to
understand and apply the control rules. Finally, the
proposed online optimal control strategy is tested and
validated through MATLAB/Simulink software and experience and apply the control rules. Finally, the
proposed online optimal control strategy is tested and
validated through MATLAB/Simulink software and
hardware-in-loop (HIL) simulation experiments. proposed online optimal control strategy is tested and validated through MATLAB/Simulink software and hardware-in-loop (HIL) simulation experiments. The contributions of this study are as follows. (1) This validated through MATLAB/Simulink software and
hardware-in-loop (HIL) simulation experiments.
The contributions of this study are as follows. (1) This
study covers the complete design and development process

hardware-in-loop (HIL) simulation experiments.
The contributions of this study are as follows. (1) This
study covers the complete design and development process
of online optimal control strategy from cycle synthesis and The contributions of this study are as follows
study covers the complete design and development
of online optimal control strategy from cycle syn
global optimization to control rule extraction. It The contribution of the complete design and development process
online optimal control strategy from cycle synthesis and
bbal optimization to control rule extraction. It provides
effective way to solve optimal calibration of online optimal control strategy from cycle synthesis and global optimization to control rule extraction. It provides an effective way to solve optimal calibration problems in application promotion for power-split HEB sy global optimization to control rule extraction. It provides
an effective way to solve optimal calibration problems in
application promotion for power-split HEB systems. It also
fully utilizes the fuel-saving capability und an effective way to solve optimal calibration problems in application promotion for power-split HEB systems. It also fully utilizes the fuel-saving capability under real operating cycles. (2) This study creates important c application promotion for power-split HEB systems. It also
fully utilizes the fuel-saving capability under real operating
cycles. (2) This study creates important conditions for the
automation implementation of cycle synth Fully utilizes the fuel-saving capability under real operating
cycles. (2) This study creates important conditions for the
automation implementation of cycle synthesis, global
optimization, and control rule extraction by u cycles. (2) This study creates important conditions for the automation implementation of cycle synthesis, global optimization. and control rule extraction by using automation implementation of cycle synthesis, global
optimization, and control rule extraction by using
reasonable mathematical methods and indicators. Thus,
this study can be an important part of big data computing automation, and control rule extraction by using
reasonable mathematical methods and indicators. Thus,
this study can be an important part of big data computing
platform in the future, which will create the possibility of reasonable mathematical methods and indicators. Thus,
this study can be an important part of big data computing
platform in the future, which will create the possibility of
online automatic calibration of vehicle control s this study can be an important part of big data computing
platform in the future, which will create the possibility of
online automatic calibration of vehicle control strategy.
The rest of this paper is organized as follow

platform in the future, which will create the possibility of online automatic calibration of vehicle control strategy.
The rest of this paper is organized as follows. Following the introduction, Section 2 describes the pow the introduction, Section 2 describes the power-split system The rest of this paper is organized as follows. Followin
the introduction, Section 2 describes the power-split syste
configuration. Section 3 presents the typical driving cyc
synthesis based on historical operation data. T Figure 2 describes the power-split system
The rest of the rest of the power-split system
Infiguration. Section 3 presents the typical driving cycle
Inthesis based on historical operation data. The DP-based
the control stra the introduction. Section 3 presents the typical driving cycle
synthesis based on historical operation data. The DP-based
rule control strategy (RCS, DP-RCS) is presented and
implemented in Section 4. Section 5 validates t synthesis based on historical operation data. The DP-based
rule control strategy (RCS, DP-RCS) is presented and
implemented in Section 4. Section 5 validates the online
optimal control strategy under the synthesized cycle. rule control strategy (RCS, DP-RCS) is presented and implemented in Section 4. Section 5 validates the online optimal control strategy under the synthesized cycle. Section 6 presents the conclusion of the study.

2. POWER-SPLIT HEB SYSTEM

The main parts of the hybrid powertrain system include an engine, two PG sets, two motor/generator (M/G) sets, and a battery package. The PG1 set is the power-split device, and the PG2 set is the reducer given its fixed ri The main part of the hybrid power-split device, and a battery package. The PG1 set is the power-split device, and the PG2 set is the reducer given its fixed ring gear. The engine output shaft is connected to the carrier of battery package. The PG1 set is the power-split device, and
the PG2 set is the reducer given its fixed ring gear. The
engine output shaft is connected to the carrier of PG1.
MG1 is connected to the front sun gear, whereas the PG2 set is the reducer given its fixed ring gear. The engine output shaft is connected to the carrier of PG1.
MG1 is connected to the front sun gear, whereas MG2 is connected to the rear sun gear. The ring gear of PG1 engine output shaft is connected to the carrier of PG1.
MG1 is connected to the front sun gear, whereas MG2 is
connected to the rear sun gear. The ring gear of PG1 is
connected to the carrier of PG2, which is connected to Engine variable to the front sun gear, whereas MG2 is
connected to the rear sun gear. The ring gear of PG1 is
connected to the carrier of PG2, which is connected to the
final drive. The battery package is used as the elect connected to the rear sun gear. The ring gear of PG1 is
connected to the carrier of PG2, which is connected to the
final drive. The battery package is used as the electric
energy storage. connected to the carrier of PG2, which is connected to the
final drive. The battery package is used as the electric
energy storage. final drive. The battery package is used as the electric energy storage. Final drive.

Final drive. The battery package is used as the electric package is used as the electrical drive.

The electric package is used as the electric package is used as the electric package is used as the electric

3. DRIVING CYCLE SYNTHESIS

energy storage.
3. DRIVING
This study focu strategy methodology based on the historical data of a real
vehicle and expects to achieve optimal fuel economy of
power-split HEB in different application scenarios.
Therefore, typical driving conditions are synthesized a strategy and expects to achieve optimal fuel economy of
vehicle and expects to achieve optimal fuel economy of
power-split HEB in different application scenarios.
Therefore, typical driving conditions are synthesized and
t power-split HEB in different application scenarios.
Therefore, typical driving conditions are synthesized and
the statistical and probability distribution characteristics of
driving conditions are effectively simulated to Therefore, typical driving conditions are synthesized and
the statistical and probability distribution characteristics of
driving conditions are effectively simulated to ensure that
the control strategy can be applied to s the statistical and probability distribution characteristics of driving conditions are effectively simulated to ensure that the control strategy can be applied to specific application scenarios. driving conditions are effectively simulated to ensure that
the control strategy can be applied to specific application
scenarios. driving conditions are effectively simulated to ensure that
the control strategy can be applied to specific application
scenarios.
3.1. Historical Data Analysis the scream and strategy control strategy can be applied to strategy can be applied to specific application of the specific application of the specific application of the specific application of the specific application of

3.1. Histo
Before the
constraint Before the synthesis of reaconstraint condition must be
historical operation data of reaching the HEB, the distance of one ro Constraint condition must be obtained by analyzing the
historical operation data of real vehicles. For a power-split
HEB, the distance of one round trip should be relatively
close, and the driving time may vary significant historical operation data of real vehicles. For a power-split HEB, the distance of one round trip should be relatively close, and the driving time may vary significantly with traffic congestion. Therefore, distance is sele HEB, the distance of one round trip should be relatively close, and the driving time may vary significantly with traffic congestion. Therefore, distance is selected as the France Constraint condition for the synthesis of driving cycles.
Given that each power-split HEB will wait for a long time
at the terminal station, the Chauvenet method is applied to
distinguish the starting and ending mom Given that each power-split HEB will wait for a long time
at the terminal station, the Chauvenet method is applied to
distinguish the starting and ending moments of vehicle
operation data, as shown in Figure 2. The screeni at the terminal station, the Chauvenet method is applied to distinguish the starting and ending moments of vehicle operation data, as shown in Figure 2. The screening method has a comparatively large probability in finding distinguish the starting and ending moments of vehicle operation data, as shown in Figure 2. The screening method has a comparatively large probability in finding the starting and ending moments of each cycle.
The distribution probability of the mileage obtained by

Figure 3. Probability density of mileage.

shows an approximately normal distribution, with a specific mid-value of 13.4 km. Moreover, the statistical characteristics of vehicle operation data can be used as the test standard for the synthesis of driving cycles. Li shows an approximately normal distribution, with a
specific mid-value of 13.4 km. Moreover, the statistical
characteristics of vehicle operation data can be used as the
test standard for the synthesis of driving cycles. Li characteristics of vehicle operation data can be used as the test standard for the synthesis of driving cycles. Linear regression analysis was used to determine nine significant statistical indicators that can represent th External for the synthesis of driving cycles. Linear
regression analysis was used to determine nine significant
statistical indicators that can represent the cycle
characteristic. The specific statistical indicator results regression analysis was used to determine nine significant statistical indicators that can represent the cycle characteristic. The specific statistical indicator results are shown in Table 1. statistical indicators that can represent the cycle characteristic. The specific statistical indicator results are characteristic. The specific statistic. The specific statistic. The specific statistic. The specific statistic statistical in the specific statistical in the specific statistic statistic statistical in the specific statist

3.2. Driving Cycle Synthesis Process
Clustering analysis and Markov methods are applied in the
synthesis of driving cycles to ensure the representativeness
and reduce the data processing pressure. The overall Clustering analysis and Markov methorsynthesis of driving cycles to ensure than
3.2. and reduce the data processing proflowchart is shown in Figure 4. First synthesis of driving cycles to ensure the representativeness
and reduce the data processing pressure. The overall
flowchart is shown in Figure 4. First, clustering analysis
method is performed to classify kinematic fragmen synthesis of driving cycles to ensure the representation
and reduce the data processing pressure. The overall
flowchart is shown in Figure 4. First, clustering analysis
method is performed to classify kinematic fragments a and reduce the data processing pressure. The overall method is performed to classify kinematic fragments and calculate state transition probability matrix between each classification. Then, Markov method is applied to realize the random reorganization of kinematic fragments. calculate state transition probability matrix between each classification. Then, Markov method is applied to realize the random reorganization of kinematic fragments. When the reconstructed segment reaches the mileage boun classification. Then, Markov method is applied to realize
the random reorganization of kinematic fragments. When
the reconstructed segment reaches the mileage boundary
(13.4 km), the synthesis of single cycle ends. If the the random reorganization of kinematic fragments. When
the reconstructed segment reaches the mileage boundary
(13.4 km), the synthesis of single cycle ends. If the error
between the feature vector of synthesized cycle θ the reconstructed segment reaches the mileage boundary
(13.4 km), the synthesis of single cycle ends. If the error
between the feature vector of synthesized cycle θ_i and
historical data θ_i is less than 5 %, then it (13.4 km), the synthesis of single cycle ends. If the error
between the feature vector of synthesized cycle θ_i and
historical data θ_i is less than 5 %, then it is recorded as an
option and the synthesis process is c between the feature vector of synthesized cycle θ_i and historical data θ_i is less than 5 %, then it is recorded as an option and the synthesis process is continued until the convergence condition is reached. Finally historical data θ_i is less than 5 %, then it is recorded as an option and the synthesis process is continued until the convergence condition is reached. Finally, the speed acceleration probability distribution (SAPD) a option and the synthesis process is continued until the convergence condition is reached. Finally, the speed acceleration probability distribution (SAPD) and sum of SAPD squared difference (SSD) of all synthesized cycles SAPD squared difference (SSD) of all synthesized cycles

Figure 4. Flowchart of driving cycle synthesis.
are calculated. The candidate cycle with minimum SSD is
taken as the most representative one.
Figure 5 show different classification quantities and SSD

taken as the most representative one.
Figure 5 show different classification quantities and SSD
results under numerous iterations to determine the best
classification number and convergence conditions. When Figure 5 show different classification
results under numerous iterations to
classification number and convergent
the iteration number is sufficien Figure 1 and the stations to determine the best
sults under numerous iterations to determine the best
ssification number is sufficiently large, different
ssification quantities are nearly the same, and the overall classification number and convergence conditions. When
the iteration number is sufficiently large, different
classification quantities are nearly the same, and the overall
SSD results show an approximate normal distributio the iteration number is sufficiently large, different
classification quantities are nearly the same, and the overall
SSD results show an approximate normal distribution. The
classification number does not affect the cycle classification quantities are nearly the same, and the overall
SSD results show an approximate normal distribution. The
classification number does not affect the cycle synthesis
quality under a sufficient number of observa SSD results show an approximate normal distribution. The classification number does not affect the cycle synthesis quality under a sufficient number of observations. Thus, **Classification number does not affect the cycle synthesis**
quality under a sufficient number of observations. Thus,
from the perspective of understanding for engineers, the
best classification number is 5. Meanwhile, the quality under a sufficient number of observations. Thus, from the perspective of understanding for engineers, the best classification number is 5. Meanwhile, the minimum SSD should be less than 3, which can be used as the from the perspective of understanding for engineers, the best classification number is 5. Meanwhile, the minimum
SSD should be less than 3, which can be used as the
convergence condition.
Taking the historical operating data of a power-split SSD should be less than 3, which can be used as the convergence condition.
Taking the historical operating data of a power-split HEB on the same line as input, the aforementioned method

Solvergence condition.

Taking the historical operating data of a power-split

HEB on the same line as input, the aforementioned method

is applied to complete the cycle synthesis process, and the Taking the historica
HEB on the same line a
is applied to complete t
result is shown in EB on the same line as input, the aforementioned method
applied to complete the cycle synthesis process, and the
sult is shown in Figure 6. The process takes
proximately 50 s, and the SSD of synthesized cycle is is applied to complete the cycle synthesis process, and the result is shown in Figure 6. The process takes approximately 50 s, and the SSD of synthesized cycle is 2.63. is shown in Figure 6. The process takes approximately 50 s, and the SSD of synthesized cycle is 2.63.
3.3. Evaluation and Validation of Synthesized Cycle approximately 50 s, and the SSD of synthesized cycle is 2.63.

2.63.

3.3. Evaluation and Validation of Synthesized Cycle The statistical characteristics of real and synthesized cycles

 $3.3.1$
The s The statistical characteristics of real and synthesized c
are compared to verify the rationality of the prop
method, as shown in Table 1. The results confirm the
proposed synthesis method can capture main featur are compared to verify the rationality of the proposed method, as shown in Table 1. The results confirm that the proposed synthesis method can capture main features of proposed synthesis method can capture main features of

Figure 6. Synthesis result of driving cycle.

Statistical characteristics	Real cycles	Synthesized cycle
Mean velocity: include zero velocity	17.6 km/h	$17.3 \; km/h$
Mean positive velocity	$21.6 \; km/h$	21.2 km/h
Standard deviation of velocity	11.1 km/h	11.4 km/h
Maximum velocity	56.0 km/h	55.0 km/h
Mean positive acceleration	0.35 m/s^2	0.35 m/s^2
Mean negative acceleration	-0.43 m/s ²	-0.43 m/s ²

Figure 8. SAPD of synthesized cycle.

Any point of a cycle can be
acceleration; thus, the SAPD
various working conditions
between the synthesized cycle Example 2018, thus, the SAPD is a precise expression for
rious working conditions. The comparison result
tween the synthesized cycle and real operation data is
own in Figure 7 and Figure 8. The two SAPD acceleration; thus, the Saptemannian and the Saptemannian various working conditions. The comparison result between the synthesized cycle and real operation data is shown in Figure 7 and Figure 8. The two SAPD distribution between the synthesized cycle and real operation data is shown in Figure 7 and Figure 8. The two SAPD distributions are similar. In summary, by comparing the statistical indicators and SAPD results, the synthesized shown in Figure 7 and Figure 8. The two SAPD
distributions are similar. In summary, by comparing the
statistical indicators and SAPD results, the synthesized
cycle can well represent the original operation conditions distributions are similar. In summary, by comparing the statistical indicators and SAPD results, the synthesized cycle can well represent the original operation conditions of the power-split HEB. distributions and SAPD results, the synthesized
eycle can well represent the original operation conditions
of the power-split HEB. cycle can well represent the original operation conditions
of the power-split HEB. ϵ can be considered the power-split HEB. $\frac{1}{\sqrt{1-\frac{1$ Any point of a cycle can be characterized by speed and acceleration; thus, the SAPD is a precise expression for

4. DP-RCS

Synthesized cycle can effectively represent the statistical characteristics of historical driving conditions of real vehicles. In this section, a DP optimization problem is formed and solved, which guarantees a globally op vehicles. In this section, a DP optimization problem is formed and solved, which guarantees a globally optimal solution in the synthesized cycle. The global optimization results are regarded as a reference and propose a novel extraction method of control rules based on DP resul Formula solution in the synthesized cycle. The global optimization
results are regarded as a reference and propose a novel
extraction method of control rules based on DP results to
formulate control strategies of real vehi results are regarded as a reference and propose a novel
extraction method of control rules based on DP results to
formulate control strategies of real vehicles. extraction method of control rules based on DP results to
formulate control strategies of real vehicles.
4.1. DP Control Algorithm

formulate control strategies of real vehicles.
4.1. DP Control Algorithm
The DP method is an effective optimization algorithm for Formulate control standard control with
4.1. DP Control Algorithm
solving multistage decision problems. On The DP method is an effec
solving multistage decisio
Bellman optimization prin
problem is transformed solving multistage decision problems. On the basis of Bellman optimization principle, the multistage decision problem is transformed into a series of single-stage problems. This approach simplifies the solution form of the Bellman optimization principle, the multistage decision
problem is transformed into a series of single-stage
problems. This approach simplifies the solution form of the
optimization problem. The cost function is the minimu Problem is transformed into a series of single-stage
problems. This approach simplifies the solution form of the
optimization problem. The cost function is the minimum
fuel consumption for a given HEV model on synthesized problems. This approach simplifies the solution form of the optimization problem. The cost function is the minimum fuel consumption for a given HEV model on synthesized driving cycle, as shown as follows: problems. The cost function is the minimum
fuel consumption for a given HEV model on synthesized
driving cycle, as shown as follows: fuel consumption for a given HEV model on synthesized driving cycle, as shown as follows:

$$
\begin{cases}\n\min_{u(t)} J(u(t)) \\
J(u(t)) = G(x(t_f)) + \int_0^{t_f} L(x(t), u(t), t) dt\n\end{cases} (1)
$$

 (t) _{oat}), where $x(t)$ denotes the state vector (state of charge),
denotes the control variable (battery power
 $L(x(t), u(t), t)$ is the instantaneous cost at each mor
 $G(x(t_j))$ is penalty function based on the termin
state, and t_i is the denotes the control variable (battery power P_{bat}), $L(x(t), u(t), t)$ is the instantaneous cost at each moment, $G(x(t_f))$ is penalty function based on the termination state, and t_f is the duration of the driving cycle.
Duri $G(x(t_f))$ is penalty function based on the termination
state, and t_f is the duration of the driving cycle.
During the optimization process, the following
inequality constraints are necessary: where $x(t)$ denotes the state vector (state of charge), $u(t)$ $L(x(t), u(t), t)$ is the instantaneous cost at each moment,

state, and t_f is the duration of the driving cycle.

During the optimization process, the following

inequality constraints are necessary:
 $\left\{P_{\text{bat}}(k) \in \left[P_{\text{bat,min}}, P_{\text{bat,max}}\right]\right\}$ (2) inequality constraints are necessary:

$$
\begin{cases}\nP_{\text{bat}}(k) \in \left[P_{\text{bat,min}}, P_{\text{bat,max}}\right] \\
\text{SOC}(k) \in \left[SOC_{\text{min}}, SOC_{\text{max}}\right]\n\end{cases} \tag{2}
$$

(–)
pper
wer. bounds of battery SOC, respectively; $P_{\text{bat,min}}$ and $P_{\text{bat,max}}$
denote the lower and upper bounds of battery power,
respectively.
The iterative process of dynamic programming is shown denote the lower and upper bounds of battery
respectively.
The iterative process of dynamic programming is
in Figure 9. The minimum cost function of N-th SOC_{min} and SOC_{max}

respectively.
The iterative process of dynamic programming is shown
in Figure 9. The minimum cost function of N-th step is:
 $J_{\nu}(x^i) = L_{\nu}(x^i) + g_{\nu}(x^i)$ (3) The iteration
in Figure 9.
 $J_N(x^i) = l_N(x)$ Figure 9. The minimum cost function of N-th step is:
 $f(x^i) = I_N(x^i) + g_N(x^i)$ (3)

en the minimum cost function in the $(0 \sim N$ -th) step is:

$$
J_N(x^i) = I_N(x^i) + g_N(x^i)
$$
 (3)
Then the minimum cost function in the (0 ~ N-th) step is

$$
I_n(x^i) = \min_{x \in \mathbb{R}^n} \{I_n(x^i, y_i) \mid x_n(x^i) \in I_n(F(x^i, y_i))\} \qquad (4)
$$

Then the minimum cost function in the
$$
(0 \sim N\text{-th})
$$
 step is:
\n
$$
J_{k}(x^{i}) = \min_{u_{k} \in [u_{\min}, u_{\max}]} \{l_{k}(x^{i}, u_{k}) + g_{k}(x^{i}) + J_{k+1}(F_{k}(x^{i}, u_{k}))\}
$$
\n(4)

where x^i is ith variable in the discrete state variable grid, $(id,$
 (i_k)
 (9)
 (10)
 (10) where x^i is ith variable in the discrete state variable grid,
superscript *i* is dependent on the grid dimension, $l_k(x^i, u_k)$
is the instantaneous cost, $g_k(x^i)$ is the penalty function
based on the current state x^i grid dimension, $l_k(x^i, u_k)$ $g_k(x^i)$ is the per-

based on the current state x^i , and $J_k(x^i)$ is the cost
function.
Minimum cost and optimal control variables at each
moment can be calculated on the basis of the backward based on the current state x^i , and $J_k(x^i)$
function.
Minimum cost and optimal control varia
moment can be calculated on the basis of iterative process. According to the co $\frac{1}{k}$ control variables at each
the basis of the backward
to the correspondence Minim
moment
iterative
between ment can be calculated on the basis of the backward
rative process. According to the correspondence
tween the state and optimal control variables at each iterative process. According to the correspondence between the state and optimal control variables at each between the state and optimal control variables at each

Figure 9. Iterative process of DP.
time, the optimal control path can be determined by the
forward calculation based on a certain initial state variable.

the optimal control path can be determined by the
forward calculation based on a certain initial state variable.
4.2. Control Rule Extraction Based on DP Results
Despite guaranteed optimality of the DP solution, it has a Forward calculation based on DP Results
A.2. Control Rule Extraction Based on DP Results
Despite guaranteed optimality of the DP solution, it has a
long offline calculation time and cannot be directly Despite guaranteed optimality of the DP solution, i
long offline calculation time and cannot be a
implemented in the control of real vehicles, whice
extraction method to obtain control rules. Conve Levelle guaranteed pursually example and cannot be directly
long offline calculation time and cannot be directly
implemented in the control of real vehicles, which need
extraction methods often rely on the observation of implemented in the control of real vehicles, which need
extraction method to obtain control rules. Conventional
extraction methods often rely on the observation of
researchers, which is not conducive to the application of extraction method to obtain control rules. Conventional
extraction methods often rely on the observation of
researchers, which is not conducive to the application of
optimization control rules. Thus, a new extraction metho extraction methods often rely on the observation of
researchers, which is not conducive to the application of
optimization control rules. Thus, a new extraction method
is proposed for the design of a DP-based control strat researchers, which is not conducive to the application of optimization control rules. Thus, a new extraction method is proposed for the design of a DP-based control strategy. Figure 10 shows the optimal mode distribution r optimization control rules. Thus, a new extraction method
is proposed for the design of a DP-based control strategy.
Figure 10 shows the optimal mode distribution result of DP
algorithm. On the basis of the engine state, t is proposed for the design of a DP-based control strategy. mode. The former is mainly distributed in low-speed, algorithm. On the basis of the engine state, the power-split
system can be divided into pure electric mode and hybrid
mode. The former is mainly distributed in low-speed,
small-demand torque range, whereas the latter is ma system can be divided into pure electric mode and hybrid mode. The former is mainly distributed in low-speed, small-demand torque range, whereas the latter is mainly distributed in high-speed, large-demand torque range. Th mode. The former is mainly distributed in low-speed,
small-demand torque range, whereas the latter is mainly
distributed in high-speed, large-demand torque range. The
two modes show a certain distribution trend but they al model.

Small-demand torque range, whereas the latter is mainly

distributed in high-speed, large-demand torque range. The

two modes show a certain distribution trend but they also distributed in high-speed, large-demand torque range. The two modes show a certain distribution trend but they also

Figure 10. Optimal mode distribution result.

The rule extraction of
group characteristics of the
same mode. The individual group should be removed boup characteristics of the system operating points in the me mode. The individual work points away from the oup should be removed to obtain the analysis results of oup feature, that is, the outlier detection method should group should be removed to obtain the analysis results of group should be removed to obtain the analysis results of group feature, that is, the outlier detection method should be performed. First, the following key paramet group should be removed to obtain the analysis results of group feature, that is, the outlier detection method should be performed. First, the following key parameters of the method are defined. group feature, that is, the outlier detection method should
be performed. First, the following key parameters of the
method are defined.
(1) Distance between two working points p and o: be performed. First, the following key parameters of the method are defined.
(1) Distance between two working points p and o :

- method are defined.

(1) Distance between two working points p and o:
 $d(p, o)$;

(2) kth distance far away from operating point p: $d_k(p)$; $d(p,o)$;
- (1) Distance between two working points *p*
 $d(p, o)$;

(2) kth distance far away from operating point *p*:

(3) kth distance neighborhood for point *p*: $N_k(p)$

On the basis of the preceding definition,

reachable distanc (1) Distance between two working points p and o:
 $d(p, o)$;

(2) kth distance far away from operating point p: $d_k(p)$;

(3) kth distance neighborhood for point p: $N_k(p)$.

On the basis of the preceding definition, the kth $d_k(p)$

n
a
e
s On the basis of the preceding definition, the kth reachable distance *reach-dist_k*(p , o) between points p and o is shown in Equation (5); this distance is the one with the (3) kth distance neighborhood for point *p*: $N_k(p)$.
On the basis of the preceding definition, t
reachable distance *reach-dist*_k(*p*,*o*) between points *j*
is shown in Equation (5); this distance is the one v
larger v reachable distance *reach-dist*_k(p , o) between points p and o is shown in Equation (5); this distance is the one with the larger value between the kth distance far away from operating point o and the distance b larger value between the kth distance far away from
operating point *o* and the distance between two working
points *p* and *o* :
reach-dist, (*p*,*o*) = max $\{d_1(o), d(p, o)\}$ (5) operating point *o* and the distance between two working
points *p* and *o*:
reach-dist_k(*p*,*o*)= max{ d_k (*o*), $d(p, o)$ } (5)
On the basis of the reachable distance, the local points p and q :

$$
reach\text{-}dist_{k}(p,o) = \max\{d_{k}(o), d(p,o)\}\tag{5}
$$

points *p* and *o* :
 reach-dist_k(*p*,*o*) =

On the basis

reachable densit On the basis of the reachable distance, the local

reachable density of point *p* is expressed as:
\n
$$
Lrd_k(p) = 1/\left[\frac{\sum_{o \in N_{k(p)}} reach\text{-}dist_k(p,o)}{|N_k(p)|}\right]
$$
\n(6)

 $|N_k(p)|$
hable density of point p indicates the
 $N_k(p)$ and average reachable distance The local reachable density of point *p* indicates the reciprocal of $N_k(p)$ and average reachable distance $\sum_{o \in N_{k(p)}} reach\text{-}dist_k(p,o)$. The higher the value of the local reachable density is, the higher the probability that p k(p) \sum reach-dist_k $o \in N$ local reachable
rocal of N_k (p
reach-dist (p, o) ē

reach-dist_{k(p,o)}. The higher the value of the local
reachable density is, the higher the probability that point p
belongs to the same cluster as the surrounding
neighborhood points: otherwise the higher the probability the higher the probability that point p
ame cluster as the surrounding
otherwise, the higher the probability reachable density is, the higher the probability that point p belongs to the same cluster as the surrounding neighborhood points; otherwise, the higher the probability that point p is an outlier.
Given that reverse ne

belongthe solution points; otherwise, the higher the probability
that point p is an outlier.
Given that reverse neighbors are not considered, the
outlier degree of data points is easily misjudged under that point p is an outlier.
Given that reverse neighbors are not considered, the outlier degree of data points is easily misjudged under certain data distribution conditions in the process of that point p is an outlier.
Given that reverse ne
outlier degree of data p
certain data distribution
obtaining outliers in tra The degree of data points is easily misjudged under
train data distribution conditions in the process of
taining outliers in traditional algorithm. Therefore, a
iendly relationship" model is introduced to analyze the certain data distribution conditions in the process of obtaining outliers in traditional algorithm. Therefore, a "friendly relationship" model is introduced to analyze the effect of reverse neighbors on the outliers of dat obtaining outliers in traditional algorithm. Therefore, a "friendly relationship" model is introduced to analyze the effect of reverse neighbors on the outliers of data points. The inverse kth distance neighborhood for po "friendly relationship" model is introduced to analyze the effect of reverse neighbors on the outliers of data points.
The inverse kth distance neighborhood for point p is expressed as effect of reverse neighbors on the outliers of data points. The inverse kth distance neighborhood for point *p* is
expressed as
 $N_{kk}(p) = \{o | o \in C, p \in N_k(o)\}$ (7)
Where *C* is the data set.

$$
N_{kk}(p) = \{o \mid o \in C, \ p \in N_k(o) \}
$$
\n⁽⁷⁾

Where C is the data set.

Therefore, the new density-based local outlier factor Where *C* is the data set.
Therefore, the new d
NLOF for each data poin
 $NN_k(p) = N_k(p) \bigcup N_{kk}$ NLOF for each data point is calculated as
 $NN_k(p) = N_k(p) \bigcup N_{kk}(p)$ (8)

$$
NN_k(p) = N_k(p) \bigcup N_{kk}(p)
$$
\n(8)

$$
NN_k(p) = N_k(p) \cup N_{kk}(p)
$$
\n
$$
Lrd(NN_k(p)) = \frac{\sum_{o \in NN_k(p)} Lrd_k(o)}{|NN_k(p)|}
$$
\n(9)

$$
|NN_k(p)|
$$

$$
NLOF(p) = \frac{Lrd_k(NN_k(p))}{Lrd_k(p)}
$$
 (10)

The larger the value of *NLOF* is, the lower the density of md is smaller than the average density of the points in its ighborhood, which indicates that it may be an outlier. herwise, the smaller the value of *NLOF* is, th peighborhood, which indicates that it may be an outlier.
Otherwise, the smaller the value of *NLOF* is, the lower the ensity of p but larger than the average density of the oints in its neighborhood, which indicates that Otherwise, the smaller the value of *NLOF* is, the lower the density of p but larger than the average density of the points in its neighborhood, which indicates that it is a normal point. When the value of *NLOF* is clo Otherwise, the smaller the value of *NLOF* is, the lower the density of p but larger than the average density of the points in its neighborhood, which indicates that it is a normal point. When the value of *NLOF* is clo density of p but larger than the average density of the points in its neighborhood, which indicates that it is a normal point. When the value of $NLOF$ is close to 1, p is equivalent to the density of points in the nei normal point. When the value of *NLOF* is close to 1, p is equivalent to the density of points in the neighborhood, which belongs to the same cluster.
After eliminating the aforementioned outliers, convex envelope algor equivalent to the density of points in the neighborhood, The larger the value of *NLOF* is, the lower the density of p and is smaller than the average density of the points in its neighborhood, which indicates that it may be an outlier.

which belongs to the same cluster.
After eliminating the aforementioned outliers, convex
envelope algorithm (Wang *et al.*, 2015) can be used to
obtain outer envelope points of the remaining working After eliminating the aforement
envelope algorithm (Wang *et al.*,
obtain outer envelope points of t
points. The lower boundary of the envelope algorithm (Wang *et al.*, 2015) can be used to obtain outer envelope points of the remaining working points. The lower boundary of the hybrid mode and the upper boundary of the pure electric mode are finally deter points. The lower boundary of the hybrid mode and the upper boundary of the pure electric mode are finally determined, as shown in Figure 11. When the demand torque at current velocity is less than the lower boundary, point upper boundary of the pure electric mode are finally determined, as shown in Figure 11. When the demand torque at current velocity is less than the lower boundary, the system operates in pure electric mode. When the determined, as shown in Figure 11. When the demand
torque at current velocity is less than the lower boundary,
the system operates in pure electric mode. When the
demand torque is greater than the upper boundary of pure
el demand torque is greater than the upper boundary of pure the system operates in pure electric mode. When the demand torque is greater than the upper boundary of pure electric mode, the system operates in hybrid mode. By extracting the control rules of the algorithm and demand torque is greater than the upper boundary of pure
electric mode, the system operates in hybrid mode.
By extracting the control rules of the algorithm and
extending it to the original OOL RCS (OOL-RCS), the fuel

electric mode, the system operates in hybrid mode.
By extracting the control rules of the algorithm and
extending it to the original OOL RCS (OOL-RCS), the fuel
economy can be further improved and directly applied to By extracting the control rules of the algorithm
extending it to the original OOL RCS (OOL-RCS), the
economy can be further improved and directly appl
the control of real vehicles. extending it to the original OOL RCS (OOL-RCS), the fuel economy can be further improved and directly applied to the control of real vehicles. economy can be further improved and directly applied to the control of real vehicles.

5. SIMULATION AND ANALYSIS

5. SIMULATION AND .
5.1. Offline Simulation 5. SIMULATION AND ANALYSIS

The simulation model
based on synthesized of
Simulink platform to va
the power-split HEB sy based on synthesized cycle is established on MATLAB/
Simulink platform to validate DP-RCS. The parameters of
the power-split HEB system are shown in Table 1. In the
simulation the HEB speed follows the cycle well, and the Simulink platform to validate DP-RCS. The parameters of the power-split HEB system are shown in Table 1. In the simulation the HEB speed follows the cycle well, and the SOC stays balanced, as shown in Figure 12 and Figure the power-split HEB system are shown in Table 1. In the simulation the HEB speed follows the cycle well, and the SOC stays balanced, as shown in Figure 12 and Figure 13. Subsequently, the operating points of engine under t simulation the HEB speed follows the cycle well, and the SOC stays balanced, as shown in Figure 12 and Figure 13.
Subsequently, the operating points of engine under the DP algorithm and DP-RCS are shown in Figure 14. The

SOC stays balanced, as shown in Figure 12 and Figure 13.
Subsequently, the operating points of engine under the
DP algorithm and DP-RCS are shown in Figure 14. The
distributions of engine operating points under two Subsequently, the operating points of engine under the
DP algorithm and DP-RCS are shown in Figure 14. The
distributions of engine operating points under two
strategies are generally consistent, which verify the Subsequently, the operating points in Figure 14. The
Subsequently and DP-RCS are shown in Figure 14. The
stributions of engine operating points under two
ategies are generally consistent, which verify the
proximate optimal distributions of engine operating points under two
strategies are generally consistent, which verify the
approximate optimal control effect of DP-RCS.
Fuel economy is the most concentrated indicator of strategies are generally consistent, which verify the approximate optimal control effect of DP-RCS.
Fuel economy is the most concentrated indicator of

approximate optimal control effect of DP-RCS.
Fuel economy is the most concentrated indicator of
power-split HEB system. The improvement of fuel
economy can be used to validate the optimal effect of DP-Fuel economy is the most concentrated in
power-split HEB system. The improvement
economy can be used to validate the optimal effects.
RCS. The OOL-RCS commonly used in engine wer-split HEB system. The improvement of fuel
ponomy can be used to validate the optimal effect of DP-
CS. The OOL-RCS commonly used in engineering, DP economy can be used to validate the optimal effect of DP-RCS. The OOL-RCS commonly used in engineering, DP $R_{\rm c}$ and $R_{\rm c}$ commonly used in equation $\frac{1}{2}$

algorithm, and Table 2.
economy. The comparison results are shown in Table 2.
The terminated battery SOC of all strategies under
synthesized cycle are close to 50 %. Under this condition,
in comparison with OOL-RCS, DP alg The terminated battery SOC of all strategies under
synthesized cycle are close to 50 %. Under this condition,
in comparison with OOL-RCS, DP algorithm can obtain
the best fuel economy, and the fuel consumption per 100 synthesized cycle are close to 50 %. Under this condition,
in comparison with OOL-RCS, DP algorithm can obtain
the best fuel economy, and the fuel consumption per 100
km is decreased by 9.0 %. The fuel consumption per 100 in comparison with OOL-RCS, DP algorithm can obtain
the best fuel economy, and the fuel consumption per 100
km is decreased by 9.0 %. The fuel consumption per 100
km of DP-RCS is decreased by 7.0 %, which is close to the best fuel economy, and the fuel consumption per 100 km is decreased by 9.0 %. The fuel consumption per 100 km of DP-RCS is decreased by 7.0 %, which is close to the results of DP algorithm.
5.2. HIL Simulation km of DP-RCS is decreased by 7.0% , which is close to the results of DP algorithm.
5.2. HIL Simulation
A HIL experiment is performed to evaluate the real-time Figure 13. SOC in simulation.
algorithm, and DP-RCS are selected to compare the fuel
economy. The comparison results are shown in Table 2.
The terminated battery SOC of all strategies under

5.2. HIL Simulation
A HIL experiment is performance of DP-RCS ¹ A HIL experiment i
performance of DP-
HIL experiment ben performance of DP-RCS. Figure 15 shows a photo of the

Figure 14. Comparison of engine operating points.

Control algorithm	Initial/ terminated SOC $(\%)$	Fuel consumption (L/100 km)	Ratio of fuel saving $(\%)$
OOL-RCS	50.00/49.95	19.81	
DP	50.00/50.00	18.02	9.0
DP-RCS	50.00/49.96	18.43	7.0

VCU mainly communicates with the dSPACE simulator via CAN bus. The vehicle and driver models are integrated dSPACE simulator is the real-time simulation platform.
The LVPS supplies 24 volt DC voltage for the VCU. The
VCU mainly communicates with the dSPACE simulator
via CAN bus. The vehicle and driver models are integrated The LVPS supplies 24 volt DC voltage for the VCU. The VCU mainly communicates with the dSPACE simulator via CAN bus. The vehicle and driver models are integrated and uploaded to the dSPACE simulator, whereas the VCU mainly communicates with the dSPACE simulator
via CAN bus. The vehicle and driver models are integrated
and uploaded to the dSPACE simulator, whereas the
control strategy is uploaded to the VCU. via CAN bus. The vehicle and driver models are integrated
and uploaded to the dSPACE simulator, whereas the
control strategy is uploaded to the VCU.
Figure 16 and Figure 17 show the velocity and SOC and uploaded to the dSPACE simulator, whereas the control strategy is uploaded to the VCU.
Figure 16 and Figure 17 show the velocity and SOC simulation results of DP-RCS based on synthesized cycle the dSPACE simulator, vehicle control unit (VCU), low-
voltage power supply (LVPS), and monitoring device. The

control strategy is uploaded to the VCU.
Figure 16 and Figure 17 show the velocity and SOC
simulation results of DP-RCS based on synthesized cycle
are shown in. On the basis of the communication protocol, Figure 16 and Figure 17 show the ve
simulation results of DP-RCS based on s
are shown in. On the basis of the commun
the resolution of the battery SOC signal Figure 11 and Figure 17 and Figure 18 and Society
Figure 18 and Society and Society and Society and Society and Society
Figure 18 and Society SOC signal is set to 0.4 %.
Society and Society and Society and Society and Soci are shown in. On the basis of the communication protocol, the resolution of the battery SOC signal is set to 0.4 %. Therefore, the SOC signal acquired from the CAN bus exhibits a stepwise change. The simulation results s the resolution of the battery SOC signal is set to 0.4 %.
Therefore, the SOC signal acquired from the CAN bus
exhibits a stepwise change. The simulation results show
that the velocity follows the synthesized cycle well, an Therefore, the SOC signal acquired from the CAN bus
exhibits a stepwise change. The simulation results show
that the velocity follows the synthesized cycle well, and the
SOC maintains balance. exhibits a stepwise change. The simulation results show
that the velocity follows the synthesized cycle well, and the
SOC maintains balance.
The fuel consumption of power-split HEB under that the velocity follows the synthesized cycle well, and the
SOC maintains balance.
The fuel consumption of power-split HEB under
synthesized cycle is 18.81 L/100 km. The fuel

SOC maintains balance.
The fuel consumption of power-split HEB under
synthesized cycle is 18.81 L/100 km. The fuel The fuel consumptif synthesized cycle is synthesized cycle is 18.81 L/100 km. The fuel

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Figure 18. Comparison of engine operating points under
two platforms.
consumption of DP-RCS is slightly deviated from the

offline simulation result but is generally close to the offline simulation result. This finding is due to the signal accuracy and response delay caused by real-time transmission and implies that the DP-RCS can obtain appro simulation result. This finding is due to the signal accuracy
and response delay caused by real-time transmission and
implies that the DP-RCS can obtain approximate optimal
control effect under real-time conditions. Figure and response delay caused by real-time transmission and
implies that the DP-RCS can obtain approximate optimal
control effect under real-time conditions. Figure 18 shows
the operating points of the engine in offline and HI the operating points of the engine in offline and HIL simulations. The HIL simulation results are generally consistent with the offline simulation results, and only the operating points of the engine in offline and HIL simulations. The HIL simulation results are generally consistent with the offline simulation results, and only minimal deviations occur due to signal accuracy and onlin simulations. The HIL simulation results are generally consistent with the offline simulation results, and only minimal deviations occur due to signal accuracy and online transmission speed. shows consistent with the offline simulation results, and only
minimal deviations occur due to signal accuracy and online
transmission speed. consistent with the original accuracy and online
minimal deviations occur due to signal accuracy and online
transmission speed.
6. CONCLUSION transmission speed.
6. CONCLUSION transmission speed.

6. CONCLUSION

This study proposes an online optimal control strategy simulation result. This finding is due to the signal accuracy

6. CONCLUSION

methodology for power-split HEB based on historical data.
Cluster analysis and Markov chain method are applied to synthesize driving cycles, which can reduce the pressure on data processing. The results show that the synth Cluster analysis and Markov chain method are applied to synthesize driving cycles, which can reduce the pressure on
data processing. The results show that the synthesized
cycle can well represent the real operating characteristics
of specific application scenarios. The DP algor synthesized
data processing. The results show that the synthesized
cycle can well represent the real operating characteristics
of specific application scenarios. The DP algorithm is
selected for offline global optimization Explore the results of specific application scenarios. The DP algorithm is selected for offline global optimization to minimize the overall fuel consumption. of specific application scenarios. The DP algorithm is
selected for offline global optimization to minimize the
overall fuel consumption.
A novel control rule extraction method is implemented selected for offline global optimization to minimize the overall fuel consumption.
A novel control rule extraction method is implemented

Selected for the consumption.
A novel control rule extraction method is implemented
to extract the control rule from the DP solution. The
extracted information is then combined with OOL-RCS to A novel control rule ex
to extract the control rule
extracted information is the extract the control rule from the DP solution. The tracted information is then combined with OOL-RCS to extracted information is then combined with OOL-RCS to

which is conducive to the understanding of engineers and
application of optimal control rules. Finally, the DP-RCS is
compared with DP algorithm and OOL-RCS. The results
show that DP-RCS based on synthesized cycle can obta application of optimal control rules. Finally, the DP-RCS is compared with DP algorithm and OOL-RCS. The results show that DP-RCS based on synthesized cycle can obtain the approximate optimal control effect to DP results, compared with DP algorithm and OOL-RCS. The results
show that DP-RCS based on synthesized cycle can obtain
the approximate optimal control effect to DP results, with
fuel saving of 7 %. The HIL simulation test shows that t show that DP-RCS based on synthesized cycle can obtain the approximate optimal control effect to DP results, with fuel saving of 7 %. The HIL simulation test shows that the proposed online optimal control strategy has good proposed online optimal control strategy has good realthe approximate of 7 %. The HIL simulation test shows that the proposed online optimal control strategy has good real-
time performance.
In conclusion, the online optimal control strategy

proposed online optimal control strategy has good real-
time performance.
In conclusion, the online optimal control strategy
methodology proposed in this work provides a reference proposed on line of the calloration propietin for power-spilt rights, In conclusion,
methodology prop
for solving the cal
which give full pla In conclusion, the original conclusion is work provides a reference

In color of power-split HEBs,

Inch give full play to the fuel-saving potential in various

in ving cycles. Moreover, the proposed methodology is an methodology proposed in the provider specific states.

which give full play to the fuel-saving potential in various

driving cycles. Moreover, the proposed methodology is an

important part of the future big data computing which give full play to the fuel-saving potential in various
driving cycles. Moreover, the proposed methodology is an
important part of the future big data computing platform,
which creates possibilities for online automat driving cycles. Moreover, the proposed methodology is an important part of the future big data computing platform, which creates possibilities for online automatic optimization and calibration of control strategies. mportant part of the future big data computing platform,
which creates possibilities for online automatic
optimization and calibration of control strategies. important part of the future big data computing platform,

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