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Configuration optimization for improving fuel efficiency of power split hybrid powertrains with a single planetary gear

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HIGHLIGHTS

- Power split hybrid powertrain configurations are comprehensively analyzed.
- A hierarchical topological graph approach is leveraged.
- Powertrain configuration modelling is automated.
- A configuration pool with all the possible designs is obtained.
- Acceleration performance and fuel economy are comparatively examined.

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ABSTRACT

In order to significantly reduce vehicular fuel consumption and emission pollutants, power-split hybrid electric vehicles are increasingly deployed to ensure that internal combustion engines work at their high-efficiency regions. Because of multiple power components (internal combustion engine, two electric machines, and a driveshaft to the wheels), configurations of such vehicular powertrains are typically very complicated. In order to systematically analyze and design a fuel-optimal powertrain, an innovative hierarchical topological graph approach is proposed. This method comprises four major design processes: (1) modeling of hybrid vehicle powertrain systems, (2) generation of a configuration pool, (3) identification of isomorphism, and (4) classification of configuration modes. Potential power-split hybrid vehicle designs are rigorously examined via a dynamic programming algorithm to estimate their acceleration performance (0–100 km/h) and fuel economy in various driving cycles.

1. Introduction

Changes to the automobile industry are urgently needed to address existing problems such as energy shortage and air pollution. Hybrid electric vehicles seem to be one of the most promising short-term solutions [1–4]. Based on their propulsion configurations, hybrid electric vehicles can be mainly divided into three categories: parallel, series, and power-split hybrids [5,6]. Power-split hybrid powertrain systems contain planetary gear sets with multiple degrees of freedom and two electric machines. The engine speed and torque of power-split hybrid powertrains are decoupled from the wheels. This allows the engine to operate at more efficient points. Power-split hybrid vehicles currently dominate the hybrid vehicle market [7]. They include models such as the Lexus RX400h, Toyota Highlander and Prius, and "dual mode" hybrid vehicles such as the Chevrolet Tahoe and Silverado Hybrids (General Motors Company, USA, GM), among many others [2,4,8–11].

Owing to very high market demand, power-split hybrid vehicle powertrain systems have become a hot topic of research. However, powertrain system design is rather complicated and needs to consider multiple intricate factors [3,4,6,12]. In his articles, Kum et al. [13,14] reported that when designing hybrid vehicles, it is very important to consider their configurations, powertrain system parameters, and intended driving cycles. Zhang *et al.* [15] obtained a new multi-mode hybrid vehicle architecture by increasing or decreasing the number of

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Table 1
Graphic model symbology.

Symbol	Representation of components	Symbol	Representation of components
○	Input or output power components	◄- - - -	Internal engagement between the gears
●	Planetary gears and vehicle frame	——	Connection between planetary gears and input/output components
◄- - -►	External engagement between the gears	━━	Components sharing a rotational center
‖	Single joint rotary	- - - - -	Components connected by a clutch

clutches. For example, he analyzed the Toyota Prius with an additional clutch, and the GM Volt with two fewer clutches. Powertrain configurations, powertrain system parameters, and driving cycles contain many variables, making the design of hybrid vehicles extremely challenging. Clearly, there is a need for a comprehensive and systematic method for designing hybrid vehicles.

According to different powertrain system kinematics and the power flow of the components, some modeling methods for hybrid vehicles have been proposed. For example, in the *lever method*, which is based on a single planetary gear, Zhang *et al.* [16,17] modeled multi-mode hybrid vehicle powertrain systems after adding clutches and brakes, and used a similar idea to design more complex hybrid vehicles. Zhuang *et al.* [18,19] applied the method to design hybrid vehicles with three rows of planetary gear sets. Compared with hybrid vehicles using transmission systems with two rows of planetary gears, those with three rows of planetary gears have advantages in terms of power dynamics, but have little advantage in fuel efficiency. Kum *et al.* [13,20] used the lever approach, while also considering design configurations, parameters, and working conditions. From these studies [21–25], it is generally acknowledged that the number of planetary gear sets directly affects the number of hybrid vehicle configurations by several orders of magnitude.

Other methods of analyzing hybrid vehicle configurations include the *bond graph* approach of Cipek *et al.* [26], who used it to analyze the power flow and efficiency of hybrid vehicle components. Bayrak *et al.* [27] improved the bond graph approach and used it to design multi-mode hybrid vehicles. In graph theory, Ngo *et al.* [28,29] adopted the planar graph approach to analyze hybrid vehicle powertrain systems based on two planetary gear sets. They varied the number of input/output power components and clutches in existing configurations to obtain an acceptable multi-mode solution. In [30], a configuration analysis of coupled planetary transmission systems for hybrid vehicles was also performed by graph modeling. However, such work was merely a preliminary attempt to use graph theory. The dynamics and kinematics of graph models were explored based on existing hybrid vehicles without sufficiently automating the modeling process. Moreover, powertrain configurations in [30] lacked a comprehensive assessment of acceleration and fuel economy performance.

The aforementioned design methods have paid little attention to systematic procedures in the design of hybrid powertrains. Therefore, the main purpose of this study is to systematically design and analyze some hybrid vehicle configurations using a novel hierarchical topological graph approach. The hierarchical topological graph approach is harnessed to analyze the kinematics and dynamics of hybrid powertrains in an automated modeling process. Identification of isomorphism and a mode classification for hybrid powertrains are presented in this paper. The dynamic performance and fuel economy of power-split hybrid vehicles are simulated by dynamic programming. Finally, a new power-split hybrid vehicle design is obtained by comparisons of a variety of the generated configurations.

This paper is organized as follows. In Section 2, we model and analyze power-split hybrid vehicles using the hierarchical topological graph method. Section 3 describes system designs and the establishment of a hybrid vehicle configuration pool. In Section 4, the kinematics of hybrid vehicles is used to identify isomorphism and classify modes. Section 5 applies metamorphic mechanism principles to existing power-split hybrid vehicles, and dynamic equations are obtained from an adjacency matrix. In Section 6, the power performance and fuel economy of power-split hybrid vehicles are analyzed by dynamic programming. Finally, in Section 7, the results are discussed, and conclusions are summarized.

2. Hierarchical topological graph modeling of hybrid vehicle powertrain

A graph is a vertex set connected by lines. Points are connected to form lines which can be used to describe relationships among things [31]. Linear graph theory [32] has been used to model and analyze hybrid vehicle powertrain systems. The topological relationships of graph theory and kinematic chain algorithms have been used to design hybrid vehicle transmission systems. In order to better describe the planetary coupling system, a hierarchical topological graph is herein proposed based on canonical graph representation [33,34]. In hierarchical topological graphs, hybrid vehicle powertrain elements (the engine (E), electric machine1 (EM1), electric machine2 (EM2), output shaft to vehicle wheel (V)) are represented by points, and the relationships between them are represented by lines. However, different components or relationships require different types of representation. Generally, a graph model of a hybrid vehicle powertrain system requires building information, logical information, hierarchical information, and isomorphism information [31].

The graph model should be able to express the topological relationships among the components, the whole structure's topology, and each component's identity. Therefore, a graph model contains various types of symbols and points. In order to express the structural relationships within hybrid vehicles more efficiently, this paper puts forward a graph model of a hybrid vehicle powertrain system, according to the symbols shown in Table 1.

The powertrain system of a 2004 Toyota Prius [35] was modeled as a hierarchical topological graph according to these modeling rules (see Fig. 1). In a hierarchical topological graph, the terms R/H/S/P represent the components of a single planetary gear set: the ring, carrier, sun and planetary gears, respectively, while G stands for the vehicle frame.

Graph theory contains many mathematical descriptions of graphs, including the adjacency matrix, association matrix, loop matrix, adjacency list, and distance matrix. The adjacency matrix provides a simple and generic mathematical description of elements' relationships in a graph model. Therefore, in this paper, an adjacency matrix is chosen to describe the topological graph model. Hybrid vehicle