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Power-Split Hybrid Electric Powertrain Design with Two Planetary Gearsets for Light-Duty Truck Applications

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Abstract: The goal of this paper is to study all feasible power-split hybrid electric powertrains with two simple planetary gearsets (PGs) that can meet light-duty truck requirements. The powertrains are explored and designed using a holistic approach, which includes automated system configuration search, automated static and dynamic equation derivation, practicality check, mode transitionability analysis, powertrain performance analyses including gradeability, launch torque, overtaking torque, 0-60mph time and fuel economy improvement potential. In the end, four two-mode power-split hybrid electric powertrains that meet all the requirements are identified.

Keywords: Hybrid Electric Vehicles, Hybrid Configurations, Powertrain Design.

1. INTRODUCTION

Fuel economy regulations for light-duty trucks in the U.S. will likely increase on average 3.5% per year from 2017 to 2021 and 5% per year from 2022 to 2025 (EPA, 2012). The National Highway Traffic Safety Administration (NHTSA) projects that fuel economy regulations can be met with the application of new technologies to conventional engines and the introduction of a higher number of hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) into the market (NHTSA, 2012). To date, automotive companies have met the current regulations with limited electrification of the small and midsize vehicle segments as well as incremental efficiency improvements in the conventional powertrain technologies. Considering the market share of light-duty trucks in the U.S. reached 38% in early 2015 (WardsAuto Corp., 2015), the automotive companies with a large share in the light-duty truck market need to consider not only incremental improvements in the conventional powertrain but also game-changing technologies such as electrification. Until now, however, they have not thoroughly addressed this problem. Therefore, work is needed to design new hybrid electric powertrains that are capable of providing both superior performance and fuel economy for light-duty trucks.

As of the end of 2014, the share of HEVs in the U.S. light-duty vehicle market is 2.8%, with 80% of these sales belonging to HEVs that use power-split powertrain architectures realized with planetary gearsets (PGs), similar to those of the Toyota Prius (WardsAuto Corp., 2015; Cobb, 2015). The remaining 20% of the HEVs belong primarily to parallel hybrid architectures. The high customer acceptance of PG-based power-split powertrains is indicative of the success of these technologies in the market and shows the need for further research to understand their full potential for light-duty truck applications.

Research in the field of hybrid electric powertrain design has focused primarily on understanding the characteristics of the existing designs. For example, the basic operating principles of General Motors' (GM) two-mode power-split hybrid architecture are explained in Grewe et al. (2007). Meisel (2009) extends this analysis by comparing the Toyota Prius hybrid architecture to GM's two-mode hybrid architecture. Kim et al. (2010) benchmark several planetary gearset (PG) based hybrid architectures in terms of fuel economy, showing the tradeoff between powertrain complexity and fuel economy improvement. Although all of these papers help understand the analysis techniques of hybrid electric powertrains and the important design criteria, they do not provide synthesis methods to help us know how to create new designs.

The first attempt to introduce PG-based hybrid electric powertrain design methodology is made by Raghavan et al. (2006). In that study, first the number of PGs, clutches, brakes and motors are determined, and then all possible kinematic combinations of these elements are analyzed using graph theory and algebraic design techniques. Vehicle performance and fuel economy, however, are not taken into account. Liu and Peng (2010) fill this gap and do take vehicle performance and fuel economy improvement potential into account in the design process. Unfortunately, they assume constant vehicle power during 0-50mph acceleration, the only acceleration criterion they consider. Zhang et al. (2014) also develop an automatic modeling and screening process that conducts an exhaustive search of all designs with different configurations, clutch locations, operating

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modes and powertrain types. They use 0-60mph time, but it is taken as the sole performance criterion and engine speed acceleration is assumed to be linearly proportional to the vehicle speed acceleration during the 0-60mph analysis. In contrast to the exhaustive design approach in Liu and Peng (2010) and Zhang et al. (2014), a generalized representation of a power-split configuration with two PGs is proposed by Cheong et al. (2011). They show that an arbitrary nonsingular kinematic relation can be realized by the proper selection of gear ratios in the generalized power-split configuration. However, whether the generalized configuration candidates are physically feasible is not investigated.

Hybrid electric powertrain design for light-duty trucks poses additional performance requirements — high towing capacity, gradeability and acceleration capability in the fully loaded condition at various vehicle speed points — which have not been addressed in the previous studies. In this paper, a holistic power-split hybrid electric powertrain design process for light-duty trucks is introduced. Similar to the approach in Liu and Peng (2010) and Zhang et al. (2014), an exhaustive search of all design modes generated by assigning powertrain components to the PG nodes is performed. The feasible transitionable power-split modes that result from this search are paired to achieve a two-mode HEV design. These mode pairs are analyzed in terms of whether they can meet light-duty truck performance requirements and their potential for improving fuel economy.

The paper is organized as follows. In Section II, an automated mode evaluation and modeling procedure is explained. In Section III, a mode screening and architecture identification process is introduced. Sections IV and V describe the algorithms that detect the transitionable and implementable mode pairs. Section VI develops the mode benchmarking criteria and related analysis methods used in the paper. Section VII presents the mode benchmarking results, including fuel economy simulations.

2. MODE EVALUATION AND DERIVATION OF STATIC AND DYNAMIC EQUATIONS

In the proposed HEV design process, the first step is to create the design space, which includes all modes that can be created with the given set of components. As the characteristics of each mode can be identified by analyzing its static and dynamic equations, the second step is to derive the equations for each mode.

2.1 Design Modes

All design modes that can be built with two PGs, one engine, one vehicle output shaft, two electric motors, one or two connections between two PGs and any brakes applied to any PG node constitute the design space of this study. The derived results, however, will be applicable to any design with any number of PGs. Each PG in a mode is represented as a lever with three nodes, each of which corresponds to ring, carrier and sun gears of the PG (Benford and Leising, 1981), as shown in Fig. 1. The lengths between ring-carrier nodes and carrier-sun nodes on the lever are taken as 1 and N_R/N_S, where N_R and N_S are the tooth numbers of ring and sun gears. In this paper, α and β represent N_R/N_S of two PGs, respectively.

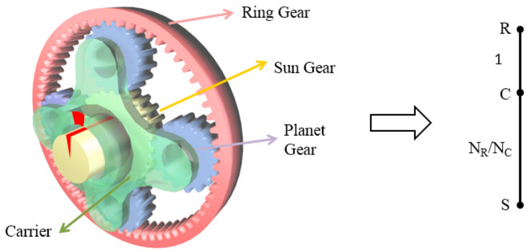

Fig. 1. Simple Planetary Gearset (Wikipedia) and its Symbolic Representation.

Since each PG has three nodes, the number of connections between two PGs varies between one and three. As three connections between two PGs create a design with one-degree of freedom — ruling out the possibility of a power-split architecture — three-connection modes are omitted. Thus, one- and two-connection modes are investigated in this study.

For the case of a single connection, any node of the first PG can be connected to any node of the second PG. Thus, 9 connection options are possible. There are five nodes to which components (engine, two electric motors, vehicle output shaft, brakes) can be assigned. The engine and output shaft cannot be assigned to the same node but electric motors can be assigned to any node. Brakes can also be assigned to any node, except for the engine and the output shaft. As a result, the total number of modes that needs to be evaluated for the case of a single connection becomes $9 \times 5 \times 4 \times 5 \times 5 \times 2^3 = 36,000$. Conducting a similar analysis for the case of two connections, $18 \times 4 \times 3 \times 4 \times 4 \times 2^2 = 13,824$ modes must be evaluated.

2.2 Derivation of Static and Dynamic Equations

All analyses applied to a design candidate in this study depend on its static or dynamic equations. The high number of design candidates requires the automatic derivation of these equations. This task is accomplished by adapting the method of (Bai et al., 2013) to HEV powertrains. The proposed procedure generates all speed and torque equations and constraints due to the brakes and connections between PGs in matrix form, thus facilitating the automation of the process. The procedure is explained using an example mode in Fig. 2. In this mode, electric motors 1&2 are connected to the ring and carrier nodes of the first PG, respectively. The vehicle output shaft, which will hereinafter be called "Wheels," is on the same node as electric motor 2. The brake on the sun gear of the first PG keeps it at zero speed. The engine, hereinafter called "ICE," is connected to the sun gear of the second PG. Rings and carriers of both PGs are connected to each other.

Automatic Derivation of Static Speed Equations The first step in deriving the static speed equation is to create the speed vector in (1) that multiplies the speed matrix. The speed vector consists of all six nodes of two PGs and the speed of the component that shares a node with another component (viz. electric motor 2). The first