

Design and Development of a Switching Roller Finger Follower for Discrete Variable Valve Lift in Gasoline Engine Applications

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ABSTRACT

Global environmental and economic concerns regarding increasing fuel consumption and greenhouse gas emission are driving changes to legislative regulations and consumer demand. As regulations become more stringent, advanced engine technologies must be developed and implemented to realize desired benefits. Discrete variable valve lift technology is a targeted means to achieve improved fuel economy in gasoline engines. By limiting intake air flow with an engine valve, as opposed to standard throttling, road-load pumping losses are reduced resulting in improved fuel economy. This paper focuses on the design and development of a switching roller finger follower system which enables two mode discrete variable valve lift on end pivot roller finger follower valvetrains. The system configuration presented includes a four-cylinder passenger car engine with an electro-hydraulic oil control valve, dual feed hydraulic lash adjuster, and switching roller finger follower. Mode switching (i.e., from low to high lift or vice versa) is accomplished within one camshaft revolution resulting in transparency to the driver. The switching roller finger follower was designed to prevent significant changes to the overhead. Load carrying surfaces at the camshaft interface were optimized including a roller bearing for low lift operation, and a diamond like carbon coated slider pad for high lift operation. Optimization focused on minimizing mass and moment of inertia while increasing stiffness to achieve desired dynamic performance in low and high lift modes. Validation test results reveal that the system meets dynamic and durability requirements.

CITATION: Zurface, A., Brownell, S., Genise, D., Tow, P. et al., "Design and Development of a Switching Roller Finger Follower for Discrete Variable Valve Lift in Gasoline Engine Applications," *SAE Int. J. Fuels Lubr.* 5(3):2012, doi: 10.4271/2012-01-1639.

INTRODUCTION

The rising cost of energy worldwide is driving an increased focus on improving energy efficiency at all points of usage. One notable focus area is improvements in the fuel efficiency of automobiles. The market drivers vary by region, governmental regulations, and consumer preferences, but the common approach is focused on improving fuel economy of automobiles in order to reduce cost of operation and reduce the consumption of fossil fuels. Technologies that improve the overall efficiency of the gasoline engine by reducing friction, pumping, and thermal losses are introduced to make the best use of the fuel within the engine. This paper describes a discrete variable valve lift (DVVL) system developed to reduce the pumping losses within the gasoline

internal combustion engine, thereby improving the fuel efficiency of the vehicle.

Strategies that utilize DVVL to reduce engine pumping losses have been studied and well documented [1,2,3,4,5]. The DVVL strategy presented here selectively allows the engine to operate on either a low lift intake valve event, or a high lift intake valve event as shown in [Figure 1](#). The low lift event reduces both lift and duration of the intake event during part throttle operation to decrease throttling losses and realize a fuel economy improvement. This is also referred to as early intake valve closing, or EIVC. When full power operation is needed, the DVVL system returns to the high lift event which is similar to a standard fixed lift event. Transitioning from low lift to high lift and vice versa occurs within one camshaft revolution. The exhaust lift event is fixed and operates as designed with either intake lift event.



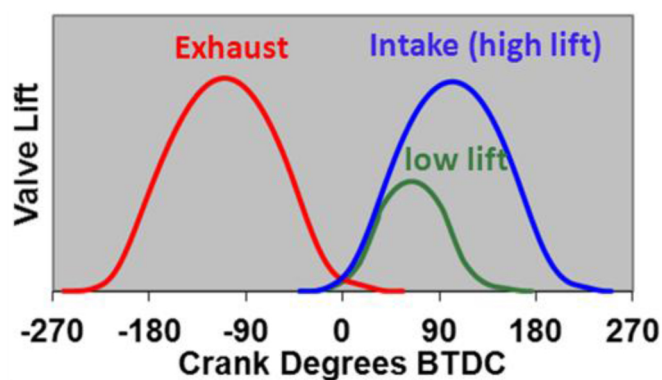


Figure 1. Variable Valve Lift Profiles.

The United States Environmental Protection Agency (EPA) showed a 4% improvement in fuel economy due to DVVL applied to various passenger car engines [6, 7]. An earlier report, sponsored by the United States Department of Energy, lists the benefit of DVVL at 4.5% fuel economy improvement [8]. Since automobiles spend most of their life at “part throttle” during normal cruising operation, a substantial fuel economy improvement can be realized when these throttling losses are minimized [2].

The DVVL approach presented in this paper is specific to a Type II valvetrain arrangement as seen in Figure 2. This configuration allows a low friction roller bearing interface for the low lift event, and retains hydraulic lash adjustment of the system for maintenance free valvetrain operation. Figure 2 also illustrates industry projections for the Type II valvetrain in automotive engines. Type II valvetrains are predicted to grow in market share and be one of the dominant valvetrains by the end of the decade [9].

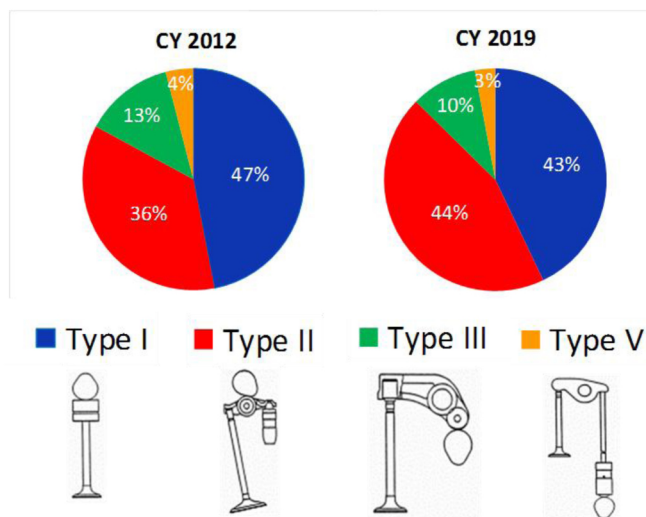


Figure 2. Projected Growth Type II Valvetrains [9].

Based on the advantages of the Type II valvetrain, a DVVL system that is based on an end pivot switching roller finger follower (SRFF) was chosen for development. The application is an in-line four cylinder gasoline engine of approximately 2.5L displacement that employs EIVC to improve fuel economy.

The SRFF based DVVL system developed for this application maintains the standard Type II architecture. The camshaft position, engine valve, and hydraulic lash adjuster (HLA) pivot point positions are common across multiple engine families. Maintaining commonality in the camshaft drive and valvetrain system for the SRFF and fixed rocker arm allows variable valve actuation (VVA) systems to be developed for DVVL or cylinder deactivation strategies while keeping the standard Type II configuration.

The primary challenges associated with developing such a system include meeting the performance and durability requirements necessary for automotive gasoline engine applications, and ensuring that the system enables mode switching within one camshaft revolution at engine speeds up to 3500 rpm. This paper details the system design, switching development, and SRFF valvetrain system optimization. Parameters that affect high speed valvetrain operation such as mechanical lash, inertia, and stiffness will be discussed.

SYSTEM DESIGN

The development of an intake DVVL system for a Type II valvetrain is presented. Figure 3 shows the intake and exhaust valvetrain layout. The exhaust valvetrain utilizes a fixed rocker arm, single lobe camshaft and a standard HLA. The DVVL intake valvetrain utilizes a SRFF, three lobe camshaft, and a dual feed HLA. The SRFF is wider than the fixed rocker arm used on the exhaust valvetrain, but both intake and exhaust share common valvetrain geometry such as the HLA pivot position, valve position, and camshaft axis. Maintaining a common geometry allowed the DVVL system to package within the existing cylinder head space without changing the overall width, height, and length of the cylinder head. Internal modifications to the cylinder head were necessary to accommodate the wider SRFF. The camshaft location with respect to crankshaft datum was unchanged, and the standard chain drive system and chain covers were utilized. Valves, valve springs, valve retainers, valve keys, and valve stem seals are also common. Implementation cost for the DVVL system was minimized by maintaining common geometries, using common components, and maintaining the standard chain drive system of the Type II valvetrain.

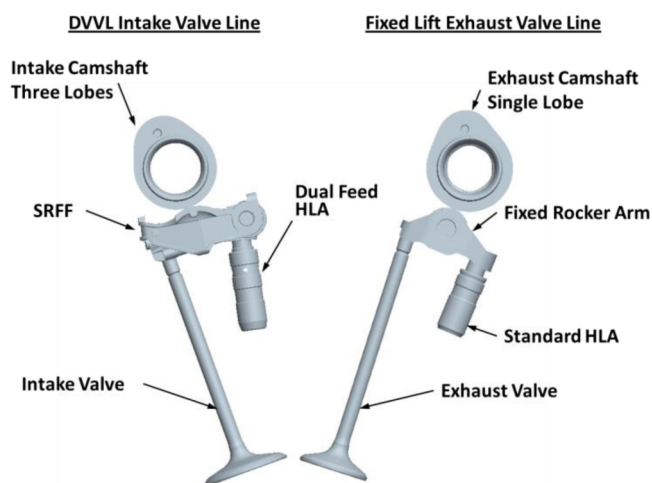


Figure 3. DVVL Intake and Exhaust Valvetrain.

Figure 4 details the major elements of the DVVL system including the intake valve, valve spring, valve spring retainer, SRFF, dual feed HLA, three lobe camshaft, and oil control valve (OCV) which is an electro-hydraulic solenoid valve. These elements work in concert to open the valve with either a high lift camshaft lobe profile or a low lift camshaft lobe profile. The high lift camshaft profile is designed to provide performance comparable to a fixed intake valvetrain. The low lift camshaft profile allows early intake valve closing to reduce pumping losses at part throttle and increases fuel economy.

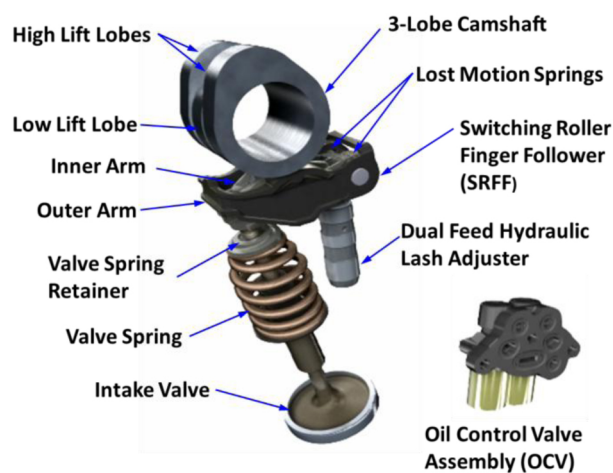


Figure 4. DVVL Intake Valvetrain.

Table 1 summarizes the pressure states in high lift and low lift modes. Hydraulic separation of the dual feed HLA lash compensation function from the SRFF switching function is also shown. The system defaults to high lift mode. In high lift mode, the OCV is off and regulates oil pressure to the control gallery and HLA upper feed. The lower feed is supplied with cylinder head gallery pressure. The engine starts in high lift mode since this is the default mode. In low

lift mode, the OCV is on. The control gallery and upper feed pressures are not regulated. The lower feed is supplied with cylinder head gallery pressure.

Table 1. High Lift and Low Lift Pressure States.

Mode	Latch Pin State	OCV Energy	HLA Upper Feed / Control Gallery Pressure	HLA Lower Feed pressure
High Lift idle - 7300 RPM	Extended	Off	OCV Regulated 0.2-0.4 Bar	Cylinder Head Gallery Pressure
Low Lift (fuel economy) idle - 3500 RPM	Retracted	On	OCV Unregulated ≥ 2.0 Bar	Cylinder Head Gallery Pressure

Low Lift Mode

The system is designed to operate from idle to 3500 rpm in low lift mode. A section view of the SRFF and the camshaft is detailed in Figure 5 and shows low lift operation. For low lift operation the OCV is energized. Oil pressure ≥ 2.0 Bar is supplied to SRFF through the control gallery and dual feed HLA. The pressure retracts the SRFF latch and the inner and outer arms become unlocked. The outer high lift camshaft lobes still contact the sliding interface on the outer arm. The outer arm rotates about the pivot axle and does not impart any motion to the valve. This is commonly referred to as lost motion. Since the low lift profile is designed for early valve closing, the SRFF must be designed to absorb all of the motion from the high lift camshaft lobes. Force from the lost motion springs ensure the outer arm stays in contact with the high lift lobe. The low lift lobe contacts the roller bearing on the inner arm and the valve is opened per the low lift early valve closing profile.

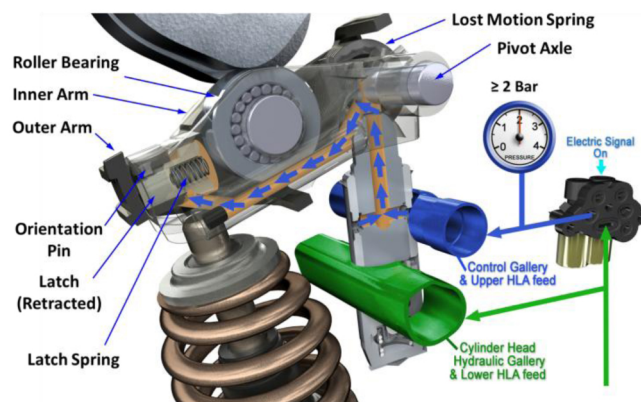


Figure 5. SRFF Assembly - Low Lift Mode.

High Lift Mode

The system is designed to operate from idle to 7300 rpm in high lift mode. A section view of the SRFF and the camshaft lobe is detailed in Figure 6 and shows high lift operation. The major components of the assembly are detailed including the inner arm and roller bearing, outer arm

and slider pads, latch, latch spring, orientation pin, pivot axle, and lost motion springs.

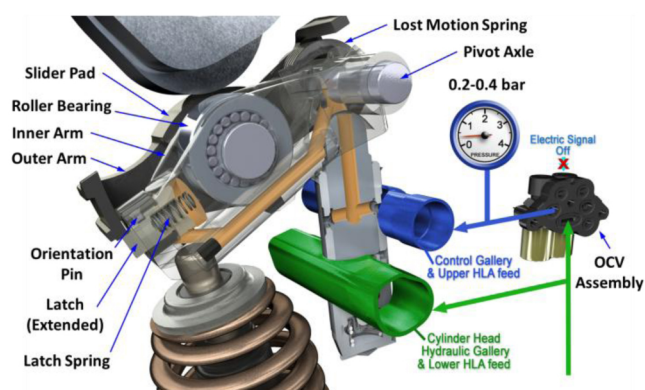


Figure 6. SRFF Assembly - High Lift Mode.

The OCV is turned off to enable high lift operation. Regulated oil pressure from 0.2 to 0.4 bar is supplied to the SRFF through the control gallery and dual feed HLA. Oil pressure at 0.2 to 0.4 bar keeps the oil passages full but does not retract the latch. The latch spring extends the latch locking the inner and outer arm. Locked arms function like a fixed rocker arm. The symmetric high lift lobes contact the slider pads on the outer arm, rotating the inner arm about the ball socket and opening the valve per the high lift profile. The slider pads are coated with diamond like carbon (DLC) coating for wear resistance and low friction. During high lift, the inner arm roller separates from the low lift lobe.

The use of OCV regulated oil pressure in conjunction with a spring biased latching mechanism selected in this system is a mature technology for VVA mechanisms. Various switching technologies are commercially available in the market [10,11,12,13].

The latch is designed with a flat latching surface. An orientation pin engages with a slot to ensure proper alignment between the flat latching surface and outer arm. A flat latch was used to reduce contact stress and minimize wear.

In high lift mode, the dual feed function of the HLA is important to ensure robustness of the valvetrain at maximum engine speeds. With the OCV off, control gallery pressure is regulated between 0.2 and 0.4 Bar. The upper feed communicates control gallery pressure between the OCV and the SRFF. The lower feed communicates cylinder head oil gallery pressure to the hydraulic lash compensation mechanism at cylinder head oil gallery pressures. The lash adjuster was designed to ensure the hydraulics have sufficient pressure for robustness to aeration and remain full of oil at all engine speeds. Hydraulic stiffness and proper valvetrain function are maintained with this system.

SWITCHING DEVELOPMENT

An important factor in the development of a DVVL system is the reliable control of switching from high lift mode to low lift mode and low lift mode to high lift mode by means

of the engine control unit (ECU) signal. The latch can only move from one state to the other during the base circle portion of the lift event when the latch is not loaded by the valvetrain. The time available for the latch movement is described as the mechanical switching window. The objective in this application was to switch within a single camshaft event up to 3500 engine rpm at temperatures of 20°C and above.

Hydraulic System

The system configuration that was chosen is shown in Figure 7. The three lobe intake camshaft with the SRFF is shown for cylinder one. The OCV and lower HLA feeds are supplied with oil from the cylinder head oil feed. The OCV assembly contains two OCVs. One OCV controls the front control gallery pressure and determines the lift mode for cylinders one and two. The second controls the rear control gallery pressure determining the lift mode for cylinders three and four.

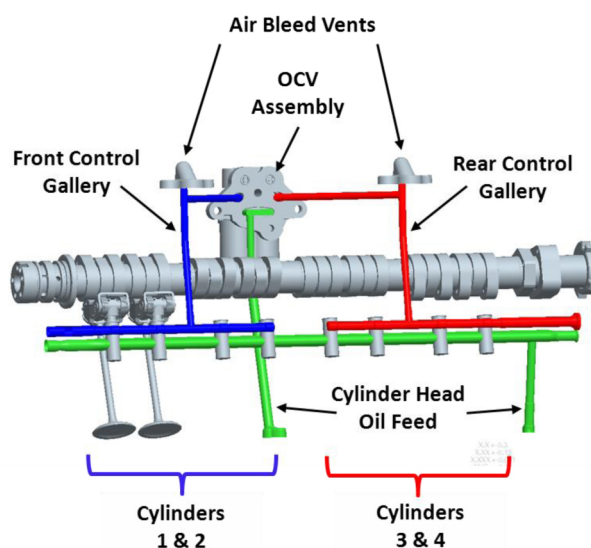


Figure 7. Cylinder Head Valvetrain And Oil Control Circuit.

Purging accumulated air in the control gallery is important to maintain hydraulic stiffness and minimize variation in the pressure rise time. Pressure rise time directly affects the latch movement time. The passive air bleed ports shown in Figure 7 were added to the high points in the control gallery to vent accumulated air into the cylinder head air space under the valve cover.

Figure 8 illustrates the intake valve timing with the corresponding OCV configurations relative to crankshaft angle for the in-line four cylinder engine. The high lift intake valve profiles are shown graphically at the top of the illustration while the lift durations are represented in bars in the lower section. The lift sequence is shown based on the OCV configurations and the firing order of the engine cylinders (2-1-3-4). Since the OCVs are configured to control