

Effects of Variable Speed Supercharging Using a Continuously Variable Planetary on Fuel Economy and Low Speed Torque

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ABSTRACT

This paper describes advances in variable speed supercharging, including benefits for both fuel economy and low speed torque improvement. This work is an extension of the work described in SAE Paper 2012-01-0704 [8]. Using test stand data and state-of-the-art vehicle simulation software, a *NuVinci* continuously variable planetary (CVP) transmission driving an Eaton R410 supercharger on a 2.2 liter diesel was compared to the same base engine/vehicle with a turbocharger to calculate vehicle fuel economy. The diesel engine was tuned for Tier 2 Bin 5 emissions. Results are presented using several standard drive cycles.

A Ford Mustang equipped with a 4.6 liter SI engine and prototype variable speed supercharger has also been constructed and tested, showing low speed torque increases of up to 30%. Dynamometer test results from this effort are presented. The combined results illustrate the promise of variable speed supercharging as a viable option for the next generation of engines.

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INTRODUCTION

Superchargers and turbochargers are competing technologies for boosting the next generation of high brake mean effective pressure (BMEP) gasoline and diesel engines. At present, turbocharging has a substantial market share advantage in the boosted engine market. However, a variable speed drive supercharger with full authority, closed loop control of boost - "boost on demand" - offers substantial advantages and the potential to push more applications toward supercharging.

The concept of a variable boost supercharger is not new. Variable boost is achieved by varying the drive speed of the supercharger independently from the engine speed, typically by use of a continuously variable transmission (CVT). The earliest example of a CVT applied to a production supercharger that the authors are aware of is the 1953 McCulloch VS57 supercharger, which used a very limited ratio range (1.09:1) rubber belt CVT [1]. Even with this very limited range, the utility of the CVT in this application was clear - more boost at low engine speeds while avoiding over-

boosting the engine or compressor surge at high engine speeds.

The McCulloch VS57 supercharger would see commercial production in the Kaiser Manhattan, Studebaker Golden Hawk and Packard Clipper, as well as use in the US performance aftermarket to the tune of roughly 46,000 total units. The VS57 would later evolve into the VR57, which used a crude ball traction drive CVT with a better, but still extremely limited, ratio range of 1.57:1 (3.5:1 low, 5.5:1 high). The VR57 managed just enough production with Ford in 1957 to homologate the supercharged engines for US NASCAR and drag racing competition (a few hundred cars), only to see the supercharger promptly banned by NASCAR after one season due to its success. [1]

Ultimately, despite the effectiveness of these units in building boost quickly, Paxton (who bought the supercharger business from McCulloch) would eliminate the CVT because the CVT technology of the time was neither durable enough nor controllable enough, even by 1960's standards. As engine maximum rpm climbed in the late 1950's and early '60's, the crude Paxton CVTs were subject to slips that ultimately led to

complete failure of the system. This was exacerbated by under hood heat, a situation that Paxton tried to remedy by moving to pressurized oil from the engine as a lubricant, to no avail [2]. The Paxton-McCullochs were intended purely as performance enhancers, but in today's marketplace, the greater driver is fuel economy improvement while maintaining or improving performance.

Engine downsizing for improved fuel economy and emissions over the last two decades has often been accompanied by some form of forced induction to maintain performance and further improve engine efficiency. While early forced induction efforts generally matched or exceeded the peak power numbers from larger naturally aspirated engines, low speed drivability often suffered as the shape of the torque curve was dramatically different.

Unlike gasoline engines, diesel engines require boost at low loads for best efficiency. A turbocharger is the most common method to add boost to the engine, but the transient response of a turbocharger tends to add perceptible lag to the engine at low engine speeds. This undesirable phenomenon is referred to as turbo lag.

To address low speed drive-ability, twin turbo and turbo + supercharger arrangements have been used, though at the expense of considerable complexity and packaging effort. The ever increasing need for fuel economy, tighter emissions and smaller engine compartments has forced engine designers to resort to increasingly exotic and costly solutions. For a turbo system, as much as a 2x increase in the heat flux is needed for catalyst light off [5]. Many conventional and unconventional methods have been tried by OEMs to deal with the under hood heat extremes characteristic of turbocharged engines. One extreme example is provided by the water cooled, aluminum alloy exhaust manifold used on the Honda RDX [4]. To deal with turbo lag, other OEMs have resorted to dual and triple turbo setups, with increasingly complex plumbing and engine controls requirements. Another option to improve turbo responsiveness is to keep the waste gate closed at light loads, but this can result in a 1% fuel economy penalty [3]. Despite the fact that this strategy only slightly improves turbo responsiveness, it is still seen as a necessary step by automakers, but the fuel economy penalty makes it an increasingly unacceptable solution.

The trend toward downsizing and down-speeding of engines works against the turbo option as well. Previously published results indicate that a 30% engine downsizing yields 33% deterioration in boost response, while a 20% reduction in engine speed results in a 50% deterioration in boost response time. [6] Furthermore, at light loads when off boost, the turbocharger is effectively an exhaust restriction for the engine that creates additional pumping losses. This is especially true when responsiveness is emphasized, resulting in a smaller, more restrictive turbo to support faster spool up. The authors recognize that reference [6] was published in 2006, and that turbochargers have continued to improve since then, e.g. electrically actuated wastegates which are open at

part load to minimize pumping losses, and improved turbo designs with better transient and low-speed performance; however these improvements are seen as incremental and not fundamental shifts in turbocharging technology.

Supercharging does not have the same lag problem as turbocharging. However, while some boost is immediately available in a supercharged engine, it is not typically the amount of boost desired at lower engine speeds because of the compromise inherent in picking a fixed drive pulley ratio to engine speed. The pulley ratio may be chosen to provide a maximum boost level, say, 7 PSI for example, but that boost level will only occur at higher engine speeds. Supercharged engines often have a lower efficiency than turbocharged engines. This is because if a supercharger with a constant drive ratio is used on an engine; the displacement of the supercharger, engine speed and the drive ratio determine the boost pressure. As the engine load decreases at a given engine speed, the supercharger outlet must be bypassed to the supercharger inlet to reduce the boost pressure. The bypassing process causes the supercharged engine to be less efficient than the turbocharged engine at the same engine speed and BMEP.

However, on the EPA light duty vehicle drive cycle, it has been shown that the supercharger's superior transient response and low end torque allows down-speeding of the engine (up-shifting at a lower engine rpm) which will improve the fuel efficiency relative to the turbocharged engine with equal peak power [8].

Additional fuel efficiency improvement can be realized by placing a CVT between the supercharger and the belt input drive. By allowing the supercharger to run independent of the engine speed, a CVT will allow the supercharger size to be matched to the peak power condition of the engine as opposed to the peak torque condition. This will enable a supercharger size reduction. The smaller supercharger is then able to run closer to the optimum isentropic efficiency area on the compressor map at low engine speeds. The CVT also allows the supercharger speed to be controlled to provide only the airflow required by the engine with little to no bypass. This could eliminate bypass losses, and result in a cooler intake charge by eliminating the recirculation of intake air through the warm supercharger housing. The improved engine efficiency is achievable only if the CVT drive efficiency is sufficiently high, and if the CVT can be controlled rapidly enough to respond to driving transients. Additionally, the system has to be practical for automotive use in terms of durability and packaging, tests that most CVT technologies fail. In this study the authors demonstrate effective reduction of by-pass utilization in the performance vehicle demonstration. In the fuel economy analysis, the only attribute of by-pass reduction evaluated was the effect of downsizing the supercharger.

For this study, the Fallbrook Technologies *NuVinci* continuously variable planetary (CVP) was used in lieu of more conventional CVT technologies. Its unique planetary kinematics [7] facilitate packaging in both thru-drive (input

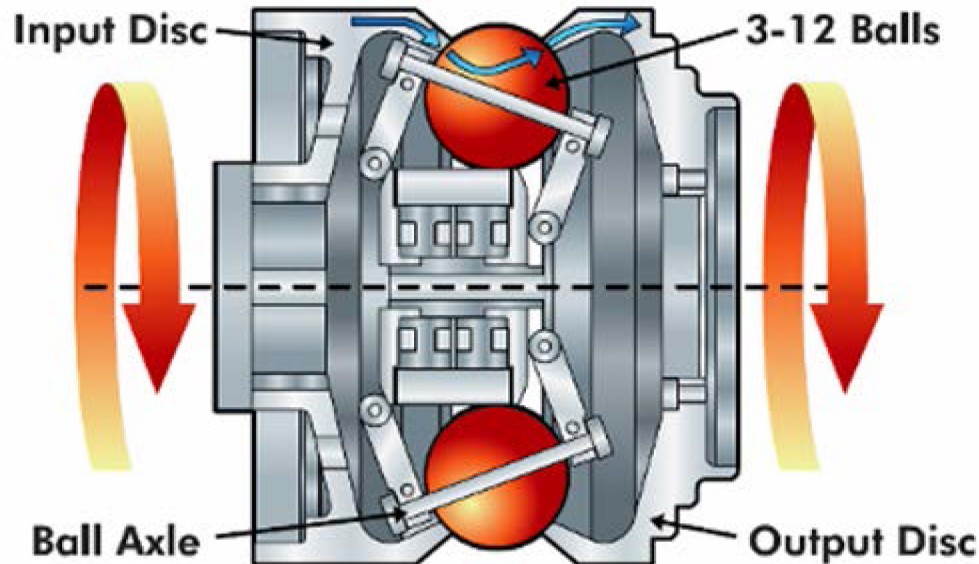


Figure 1. Thru-Drive

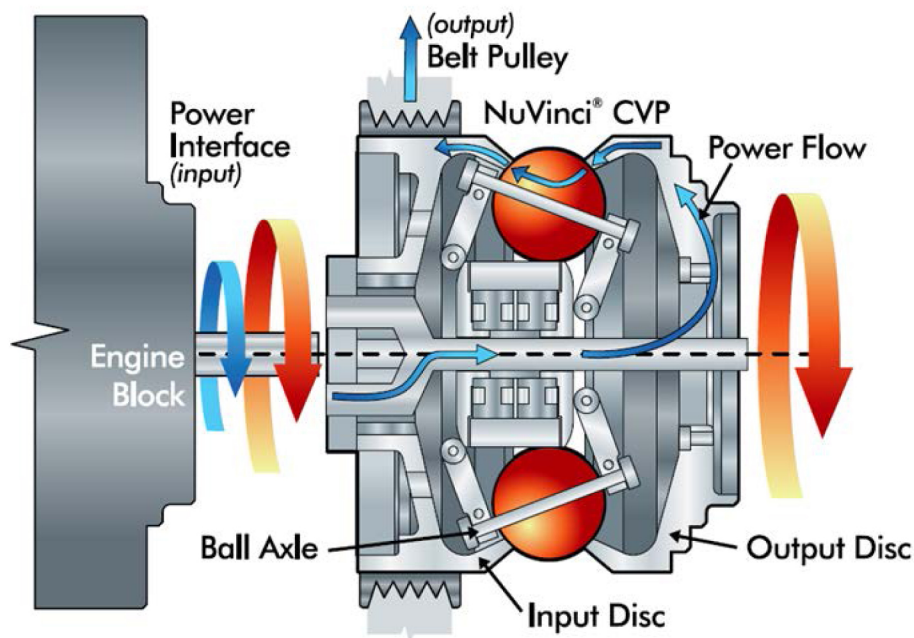


Figure 2. U-Drive

and output shafts concentric, but on opposite ends of the CVP, see [figure 1](#)) and u-drive (input and output shafts concentric and on the same side of the CVP, see [figure 2](#)) configurations, a necessity for packaging in tight under hood spaces on accessory beltlines, particularly if a one belt system is to be used.

This paper will demonstrate that a CVT-equipped supercharger not only has the potential to fix drivability issues with less under hood complexity, it also effectively turns the supercharger into a wide range variable

displacement device. In turn, the supercharger/CVT system can now be combined with other fuel-saving technologies such as cylinder cut-out or advanced combustion cycles.

PERFORMANCE

Description

As any OEM knows all too well, promising simulation and test cell data often do not translate well to real world drivability. With this in mind, Fallbrook elected to build a

variable speed supercharged demonstration vehicle with the primary objective of providing a rapid demonstration of the technology in a fully functional vehicle. The requirement to build a demonstration vehicle quickly and cost-effectively drove the choice of vehicle and supercharger to readily available options, in this case, a 2008 Ford Mustang Bullitt equipped with a 4.6 liter V8 and an aftermarket ProCharger centrifugal supercharger (PISC).

At the time of the car's construction, only the U-drive configuration of CVP was available in quantity, which also drove the choice of a centrifugal supercharger for packaging reasons. The thru drive CVP, designed from the ground up for use with Roots type supercharger, has passed OEM durability testing since this car was constructed, and will be used in future Fallbrook demonstration vehicles. A U-drive unit similar to the one used in this car is shown in [Figure 3](#) and the thru drive prototype for Roots type superchargers is shown in [Figure 4](#). The pulley ratio of the kit supplied by ProCharger was 2.06:1, to provide a nominal 7 PSI of boost at engine power peak. No other changes, aside from standard ECU recalibration, were made to the factory engine or exhaust system.



Figure 3. U-Drive Unit

After a break-in period on the fixed ratio supercharger system, to ensure that it was functioning properly, the CVP drive was installed. In this particular case the CVP was mounted to the harmonic balancer/crankshaft in place of the ProCharger's drive pulley. This results in a two belt system, with the stock belt driving the engine accessories and a dedicated belt driving the supercharger. Due to the location of the supercharger versus the other OEM accessories, a single belt system is not possible in this installation [Figure 5](#) shows the installation



Figure 4. Thru Drive



Crankshaft-mounted CVP

Figure 5. Installation of Crank-Mounted CVP for Supercharger

Once the CVP was installed, Lingenfelter Performance Engineering, a well-known performance tuner, performed fuel mapping for the engine with the new variable speed supercharger. They also improved the baseline (fixed ratio ProCharger setup) fuel mapping to produce the best possible fixed ratio drive result. Wide open throttle (WOT) performance tests (dyno pulls) were run with CVP locked at 1:1 for the baseline (at CVP ratio = 1:1 the supercharger pulley ratio was identical to the baseline ProCharger configuration) and in variable speed mode with the CVP actively changing ratio. In variable speed mode the CVP was controlled as a function of throttle position and engine speed