

A New De-throttling Concept in a Twin-Charged Gasoline Engine System

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ABSTRACT

Throttling loss of downsized gasoline engines is significantly smaller than that of naturally aspirated counterparts. However, even the extremely downsized gasoline engine can still suffer a relatively large throttling loss when operating under part load conditions.

Various de-throttling concepts have been proposed recently, such as using a FGT or VGT turbine on the intake as a de-throttling mechanism or applying valve throttling to control the charge airflow. Although they all can adjust the mass air flow without a throttle in regular use, an extra component or complicated control strategies have to be adopted. This paper will, for the first time, propose a de-throttling concept in a twin-charged gasoline engine with minimum modification of the existing system. The research engine model which this paper is based on is a 60% downsized 2.0L four cylinder gasoline demonstrator engine with both a supercharger and turbocharger on the intake. The idea is to use a CVT driven supercharger to 'throttle' the intake mass flow. By the adoption of a CVT, the supercharger outlet pressure could be controllable. Depending on whether the outlet pressure is larger than the inlet, the supercharger could supply boost at high load consuming engine power or behave like an expander under part load presenting a means to recover the throttling loss to provide all the necessary need.

A 1-D simulation model was used for this research with some experimental data of the supercharger functioned as an expander from a test rig. The results showed that at part load, by recovering some throttling loss through the supercharger, up to 3% BSFC improvement could be achieved compared to the throttled counterpart depending on the engine operating points. The effect of the reduced supercharger outlet temperature on the combustion efficiency was also discussed. It showed in the end that by the speed control, extended working range of the supercharger can be achievable which could push the fuel efficiency of the downsized engine further.

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INTRODUCTION

In our previous paper [1], a new turboexpansion concept in a twin-charged engine system was proposed to address the issue of high inlet temperature under full load whilst recovering some energy otherwise would be wasted on the exhaust.

To be more specific, the research model was equipped with a centrifugal turbocharger and a CVT driven positive displacement supercharger (see [figure 1](#)). The CVT driven supercharger at the high-pressure (HP) stage could be functioned as a normal compressor at high load and low speed, while behaving like an expander under

high load and high speed. Unlike the conventional compression mode of the supercharger, the 'expansion mode' utilized the turbocharger to over-boost the intake charge by further closing the wastegate while the supercharger by the speed control acts like a turbine expanding the over-compressed intake charge to the required plenum pressure and reducing its temperature. It is anticipated that such concept is beneficial for knock resistance due to the intake temperature reduction. From the point of energy recovery, it also provides an innovative approach which indirectly reclaims some of the otherwise wasted exhaust energy.

There are some similarities between the new turboexpansion concept and turbocharged Miller cycle. They both have larger backpressure and larger after-turbocharger-compressor pressure. The aim of both configurations is to lower the cylinder temperature at the point of ignition in order to mitigate knock at high load. However, the Miller cycle allows a reduction in effective compression ratio and transfers the compression work from the cylinder to the turbocharger compressor with the charge cooled as an intermediate stage. While the new turboexpansion concept differs from the Miller cycle by reducing the charge temperature via the high-pressure stage expander. It does not change the compression stroke and have a similar plenum pressure compared to the conventional turbocharged counterpart.

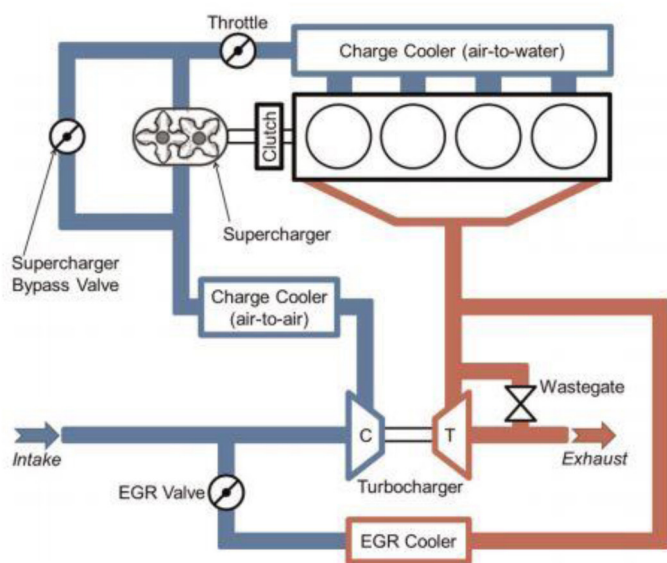


Figure 1. Schematic of a standard turbo super system [2]

The CVT driven supercharger in the new turboexpansion concept features the characteristics of recovering some over-compressed intake energy by lowering the intake pressure at high load. Analogically, the CVT supercharger can also be adopted to replace the conventional throttle for SI engines at part load to recover some throttling energy by expanding the close-to-ambient pressure (1 bar) to the required intake pressure (normally <0.5 bar). It is conceived that by reclaiming some throttling loss through the supercharger, part load fuel efficiency could be improved. In addition, the cooling effect of the supercharger expansion could lighten the load of the after-cooler which is beneficial for knock resistance and volumetric efficiency for the following possible high load cycle.

This paper will investigate the benefits of using a CVT driven supercharger as a de-throttling method for a turbo-super configuration SI engine. First, a brief literature review on various de-throttling concept are introduced, then the methodology of the new de-throttling concept utilizing a CVT driven supercharger is proposed. The test data on the supercharger functioned as an expander and how the limited test data is extrapolated are followed afterwards. In the Results section, the 1-D simulation results will be shown to investigate the advantages of the new de-throttling method. The

limitations and further work are outlined in the Discussion section in which the potential transient performance, the effect of the CVT ratio range on the de-throttling performance and the condensation effect will be pointed out.

REVIEW OF THE CURRENT DE-THROTTLING CONCEPT

A conventional throttle plate impedes fuel efficiency as it increases the engine's workload, forcing the pistons to pull air in from a low-pressure area on the intake that extends all the way to the throttling plate gateway. There are a number of de-throttling approaches which could reduce or even eliminate the use of a conventional throttle which is reviewed in the following.

Turbine Throttling [3]

Waste Energy Driven Air Conditioning System (WEDACS) is an engine load control system that provides electrical energy and cooling power by the energy that is otherwise lost in throttling. This technology patented by the Eindhoven University of Technology replaces the conventional throttle valve with a turbine-generator combination. Throttling losses are recovered through de-throttling the intake charge which decreases the load of the alternator and air conditioning compressor. In addition, the intake temperature can be reduced due to the expansion effect of the turbine. This system was demonstrated to improve the fuel efficiency by up to 19% in MVEG-A drive cycle. However, in this layout, even though the de-throttling concept is achieved, the throttle valve is still needed due to the fact that the air mass flow might be out of range for the turbine at idle. Meanwhile, a bypass throttle is also a necessary component to make it possible for the engine to operate under high load, without which the turbine would act like a restricted nozzle to constraint the intake mass flow (see figure 2).

Adopting variable nozzle turbines was demonstrated to improve the small operating range of the system by the same group of authors [4]. In their research, two variable nozzle mechanisms were used to adjust high engine power and low engine power respectively. By the optimization of the VGT mechanism, the system showed up to 8% fuel efficiency improvement for typical turbine operating conditions.

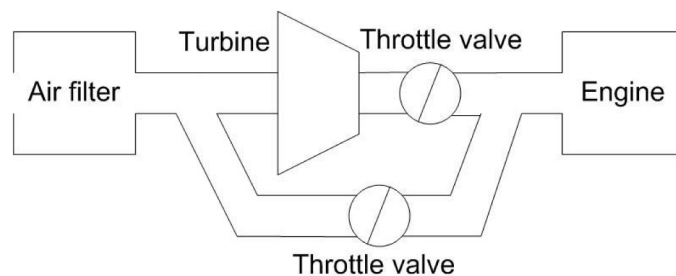


Figure 2. Air flow paths in the WEDACS system

Valve Throttling

Rather than regulating air flow via a throttle plate at the point where air enters the intake system, valve-throttling system varies the amount by controlling the flow of air at the point where it enters the engine's cylinders. Compared to the throttled counterpart, the intake manifold of the valve-throttling system remains at or near atmospheric pressure so the engine does not encounter the same resistance. This results in a reduction in the pumping loss under part load, which translates to better fuel efficiency and transient performance. It should be noted that even though the valve-throttling concept does not benefit as much for the downsized turbocharged SI engine as for the naturally aspirated engine, it shows the advantage on the transient performance as the time it takes for the turbocharger to pressurize the intake track is reduced. BMW's Valvetronic, Fiat's MultiAir and Nissan's Variable Valve Event and Lift technology are all valve-throttling concept now being adopted in current production engines.

Cylinder Deactivation

Cylinder deactivation usually referred as a method to achieve variable displacement is not a novel concept but rather has existed for decades. It allows the engine to be 'downsized' at light-load operation and offers maximum performance under full load condition. This concept generally keeps the intake and exhaust valve closed through all cycles for a particular set of cylinders in the engine. By doing so, the throttle valve is forced to be opened more fully resulting in better pumping work and accompany improved combustion chamber pressure thus better combustion efficiency. Reduced power train friction through the absence of actuating forces on the deactivated valves is also considered to contribute to the fuel consumption improvement [5].

This de-throttling concept has only been applied to relatively large displacement engines but recent research shows that it can also be applied to small displacement turbocharged SI engines. For instance,

Volkswagen implemented the cylinder deactivation concept on its four-cylinder engines. Its system named Active Cylinder Technology (ACT) stated the reduced fuel consumption in the EU driving cycle by about 0.4L per 60 miles [6]. Two issues including unbalanced cooling and vibration are generally needed to be overcome with cylinder deactivation engines.

Supercharger De-Throttling

Romagnoli *et al* conducted an experimental research on supercharger as an expander. It was considered to be the first available performance test data of an Eaton supercharger (positive displacement) acting as an expander in the public domain [7]. The authors found out that in order to deliver a similar mass flow range to the engine when it is operated as an expander, the supercharger must spin at a slower rotational speed. For example, if an expansion ratio of 1.4 was desired, in order to deliver a similar engine mass flow, the supercharger would have to spin at approximately half the speed compared to the operation as a compressor (see figure 3). In addition, when the supercharger was functioned as an expander, the isentropic efficiency dropped significantly to be around 45% as can be seen in figure 4. It is suggested that the supercharger could be functioned either as a compressor or an expander if a continuously variable transmission was installed. Since the supercharger when spinning at a relatively low speed could have an 'expansion mode', the turbine-throttling concept mentioned above could be used for reference to propose a new de-throttling concept. However, compared to the normal turbine-throttling concept which recovers some throttling loss to generate electricity via a turbine-generator combination, The supercharger de-throttling concept is also feasible to reclaim some of the otherwise wasted throttling loss through a direct connection to the crankshaft via the control of the CVT ratio. This paper will conduct a 1-D simulation to investigate the benefits of this gas exchange process.

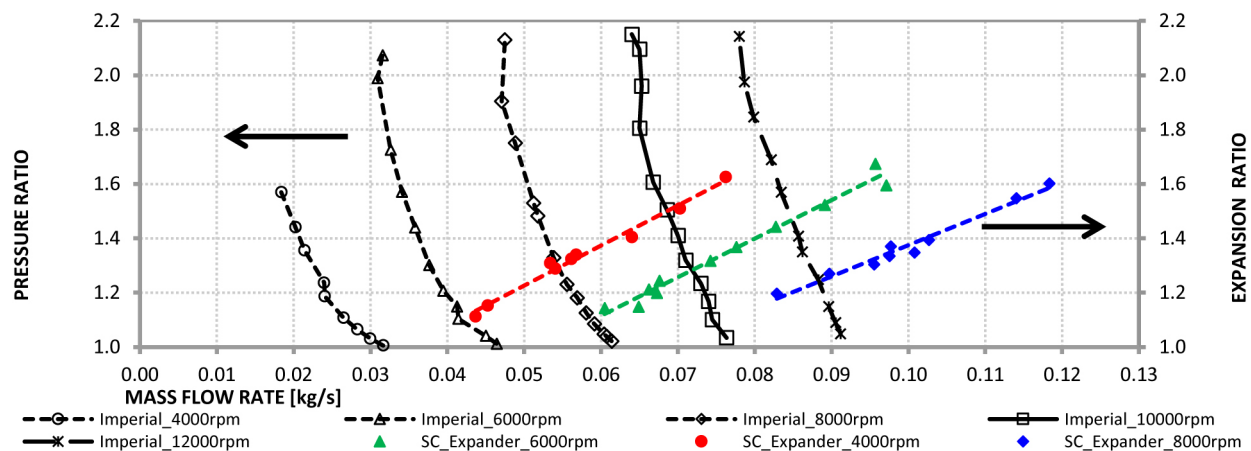


Figure 3. Pressure and expansion of Eaton Supercharger versus mass flow