

SuperGen on Ultraboost: Variable-Speed Centrifugal Supercharging as an Enabling Technology for Extreme Engine Downsizing

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ABSTRACT

The paper discusses investigations into improving the full-load and transient performance of the Ultraboost extreme downsizing engine by the application of the SuperGen variable-speed centrifugal supercharger.

Since its output stage speed is decoupled from that of the crankshaft, SuperGen is potentially especially attractive in a compound pressure-charging system. Such systems typically comprise a turbocharger, which is used as the main charging device, compounded at lower charge mass flow rates by a supercharger used as a second boosting stage. Because of its variable drive ratio, SuperGen can be blended in and out continuously to provide seamless driveability, as opposed to the alternative of a clutched, single-drive-ratio positive-displacement device. In this respect its operation is very similar to that of an electrically-driven compressor, although it is voltage agnostic and can supply other hybrid functionality, too.

In the work reported here a prototype SuperGen unit was tested on the Ultraboost extreme downsizing demonstrator engine and the performance compared to that of the originally-specified positive-displacement device. This engine has previously been described in detail and represents a 60% downsizing factor versus a 5.0 litre naturally-aspirated V8, although the 'standard' baseline combination of supercharger and turbocharger was found in earlier work to be a limitation on achieving the full downsizing factor at low engine speed.

The improvement in full-load performance in the area where the turbocharger cannot generate the required boost by itself is reported. The transient response of the combined system at low engine speed is also presented, together with part-load fuel economy data at several engine speed and load points. Finally, this part-load data is used for vehicle modelling work showing that a more-efficient high-pressure stage can bring further fuel economy benefits to extremely-downsized vehicle applications.

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INTRODUCTION

Downsizing is 'megatrend' in the automotive industry and represents the state of affairs for the spark-ignition (SI) (or Otto cycle) engine [1,2]. This is because downsizing is a proven way to improve the fuel economy of SI engines through several means, principal among which can be considered to be [1,3]:

- Reduction of the throttling losses inherent in the Otto cycle when mixture-quantity load control is conducted away from the inlet valve head, and the engine is operating with a fixed air-fuel ratio (AFR).

- Improvement of mechanical efficiency (because the ratio of indicated mean effective pressure (IMEP) to brake mean effective pressure (BMEP) increases).
- Reduction of thermal losses, which in [1] was found to be extremely important in the case of down-cylindering.
- Reduction of engine warm-up times, important when replacing an engine which is relatively lightly-loaded on the drive cycle with a downsized one [1].

Importantly, it can deliver its benefits without radically having to change the manufacturing infrastructure which has been built up over the years and also permits the use of simple and robust exhaust gas treatment (EAT) systems.

While the amount of fuel economy improvement that can be expected with a downsizing strategy can be readily estimated [4], the actual ability successfully to downsize any SI engine is a function of several limiting factors, the most important of which can be considered to be the ability to resist abnormal combustion (principally knock and preignition) and the ability of the charging system to supply the required air at the necessary response rate. In [1] a research engine, ‘Ultraboost’, is reported which permitted a downsizing factor of 60% to be realized over an advanced large-capacity naturally-aspirated (NA) engine, but which was found to be challenged in terms of its air delivery system; its positive-displacement supercharger (with a single-speed drive ratio) was suggested to be a limitation because it could not supply sufficient air to meet the aggressive 1000-1500 rpm full-load torque targets. The present paper reports the results of a research project investigating the potential to improve the full-load and transient performance of the Ultraboost extreme downsizing engine in this respect by the application of the SuperGen variable-speed centrifugal supercharger, and to gauge its effect on part-load fuel consumption.

Ultra Boost for Economy and Definition of Extreme Engine Downsizing

The Ultraboost engine was the result of a collaborative research project, ‘Ultra Boost for Economy’, funded by the Technology Strategy Board, the UK's innovation agency. This programme and its targets have been discussed in detail in several publications [1,5], and the ability of the engine to produce more than 190 bhp/l and 35 bar BMEP were shown to be key enablers of in excess of 35% improvement in in-vehicle fuel consumption (when combined with some improvements in vehicle mass, drag and the application of stop-start and no other hybridization functions being applied). This engine was found to be resistant to low-speed preignition (LSPI) and also found to be very knock-resistant and to have a low octane appetite [6]. It has also been used for cooled exhaust gas recirculation (EGR) studies [7] during which the use of cooled EGR was found to be beneficial in reducing fuel consumption at rated conditions.

These results underline that the Ultraboost engine itself would be an excellent platform for research into the extreme downsizing of SI engines. Extreme downsizing is defined here as realizing a downsizing factor of 60%, where

$$DF = \frac{V_{Swept\ NA} - V_{Swept\ Downsized}}{V_{Swept\ NA}}, \quad (1)$$

where DF is the downsizing factor, $V_{Swept\ NA}$ is the swept volume of an NA engine of a given power output and $V_{Swept\ Downsized}$ is the swept volume of a similarly-powerful downsized alternative. The Ultra Boost for Economy project used the torque curve from the Jaguar Land Rover AJ133 V8 engine [8] as a target for its 2.0 litre engine design, thus satisfying the above criterion for extreme downsizing.

The main specifications of the Ultraboost engine are shown in the Table 1. Note that this refers to the ‘UB200’ specification which had an engine-driven charging system, although the core engine was substantially unchanged throughout the project [1].

Table 1. Ultraboost engine specification (UB200 level with engine-driven charging system). Data reproduced from [1]

General architecture	4-cylinder in-line with 4 valves per cylinder and double overhead camshafts
Construction	All-aluminium AJ133 cylinder block converted to single-bank operation on the A Bank (right-hand side) Siamesed liner pack to facilitate reduced bore diameter Dedicated cylinder head
Firing order	1-3-4-2
Bore	83 mm
Stroke	92 mm
Swept volume	1991 cc
Combustion system	Pent-roof combustion chamber with asymmetric central direct injection and spark plug High-tumble intake ports Auxiliary port-fuel injection Possible second spark plug position in an under-intake-port location
Compression ratio	9.0:1
Valve gear	Chain-driven double overhead camshafts with fast-acting dual continuously-variable camshaft phasers (DCVCP) Cam profile switching (CPS) tappets on inlet and exhaust
Engine management system	Lotus ‘Euro 8’ engine control unit (ECU)
Low-pressure charging system stage	Honeywell GT30 wastegated turbocharger
Inter-stage charge air cooler	Off-engine water-cooled charge air cooler; effectiveness set to mimic typical vehicle-mounted systems
High-pressure charging system stage	Clutched Eaton R410 Roots-type supercharger with overall 5.6:1 drive ratio (later changed to 5.9:1 - see text) Full-flow supercharger bypass
After-stage charge air cooler	Water-cooled charge air cooler, mounted in the intake plenum after the main throttle

In [1] it was found that the combustion system developed for Ultraboost was more than capable of burning the air supplied to the engine efficiently, since the target torque output could easily be exceeded without encountering knock and preignition issues. This was known because a facilitated combustion air handling unit (CAHU) had been used to decouple the development of the combustion system from that of the charging system: the core engine had been tested under boosted conditions at the University of Bath at loads above which it would have to perform even when the engine

driven charging system was mounted to it (these loads allowing for the drive torque necessary to drive the supercharger selected in earlier work as a high-pressure stage [9]).

However, it was also found that, when the specified charging system was fitted, the engine could not quite supply itself with sufficient air at low speeds to generate the required torque of 400 Nm at 1000 rpm (25.1 bar BMEP). Thus the full-load performance status at the end of the Ultra Boost for Economy project is shown in [Figure 1](#) (reproduced from [1], where more detail is available on the operating conditions pertaining at that time).

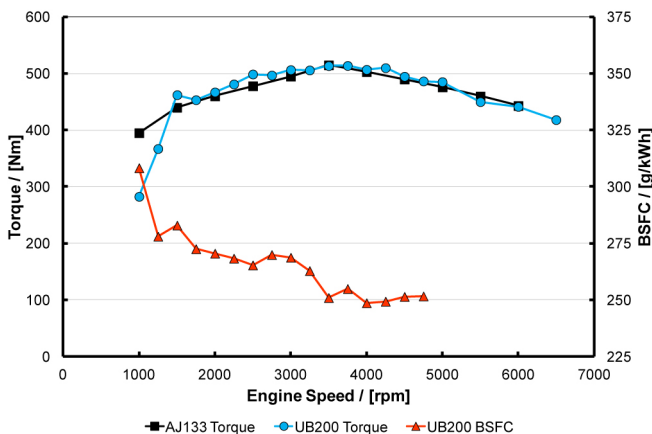


Fig. 1. Final performance of Ultraboost engine (known as UB200) versus the initial project target torque curve taken from the Jaguar Land Rover AJ133 NA 5.0 litre V8 engine. Note shortfall in torque below 1500 rpm. Reproduced from [1]

The slight miss on low-speed performance was found to be the case despite some minor reconfiguration of the charging system in the form of shortening the supercharger drive ratio, there having been found to be a strong interaction between the high-pressure supercharger and the low-pressure turbocharger stages. Much effort had been expended within the project in selecting the components used in the charging system [9], and subsequent analysis was also undertaken to understand why they failed to deliver the desired charge air conditions.

The present work was undertaken to investigate whether SuperGen, a novel type of supercharger, could replace the positive-displacement Eaton R410 Roots-type high-pressure device and deliver improved full-load performance and transient response, and to gauge its effect on brake specific fuel consumption (BSFC) at various boosted minimap engine operating points.

THE SUPERGEN VARIABLE-SPEED CENTRIFUGAL SUPERCHARGER

The finally-selected charging system for the Ultraboost project had the components described in [Table 1](#), these being selected since they represented production technologies which could be sourced readily. Copeland et al. [9] described the process by which these devices had been chosen, and also described some alternative technologies, one of which was the use of the SuperGen supercharger in the high-pressure stage position. This technology showed considerable promise in this

application but was not carried into the main Ultraboost project because of the desire to keep all of the technologies as near to mass-producible as possible. Nevertheless, it was always considered that SuperGen, when employed as a high-pressure stage, could perhaps deliver better driveability through its variable-ratio characteristic.

In the work reported here a prototype SuperGen unit was tested on the Ultraboost extreme downsizing demonstrator engine. SuperGen varies the drive ratio between its centrifugal compressor output stage and its input pulley by using a power-split gearbox and two electric machines, which divide the input torque, transmit it via two paths (mechanically and electrically) and then recombine it in order to decouple the speed of the compressor from that of the crankshaft.

Its variable ratio characteristic is especially attractive in a compound pressure-charging system where a turbocharger is used as a low-pressure device (capable of solely providing the boost required at high speed and load) and a supercharger is used as a high-pressure stage at lower charge mass flow rates,

SuperGen uses an electromechanical power-split transmission system to provide an ‘on-demand’ boosting system with potential hybrid capabilities. It is primarily intended to be used in series with a turbocharger for both gasoline and diesel engines to provide similar map width to series turbocharger systems while improving transient response, with further possibilities to use it as a sole boosting device on lower-specific output engines. The electrical transmission path provides response, controllability and refinement since it can be blended in and out continuously to provide seamless driveability. In this respect its performance is similar to that of an electrically-driven compressor (also known as an ‘e-supercharger’ or ‘e-booster’). However, the parallel mechanical path greatly reduces the size and cost of the electrical components necessary to produce the required boosting range while increasing efficiency and enabling steady-state, charge-neutral operation.

The unit typically replaces the alternator on an engine front-end accessory drive (FEAD), facilitating packaging in a wide range of applications (although the use of a dedicated drive is also possible). Furthermore, when equipped with appropriate internal clutches, there are opportunities for significant synergies with micro- and mild-hybrid architecture and functions. These are not investigated in the present work. Because the primary work input to the device is a mechanical one from the crankshaft, it is voltage agnostic and can thus provide all of this functionality while only requiring a 12 V electrical architecture in the vehicle. As such it can help provide a bridge to 48 V electrical architectures on board vehicle platforms from existing 12 V ones.

System Overview

[Figure 2](#) shows the current SuperGen design level. Power is input to a pulley (1) via a FEAD drive from the crankshaft. The input shaft carries the rotor (2) of electrical machine E1 and drives the annulus of an epicyclic traction-drive gearset (4). The rotor (5) of a second electrical machine (E2) is connected to the planet carrier of the gearset (4) and is supported on bearings (6). The sun shaft of the

gearset passes through the centre of the rotor (5) and is connected to a radial flow impeller (7). The device is plumbed into the engine cooling system (9) for cooling. The motors are permanent magnet (PM) devices, and E1 functions as a belt-driven integrated starter-generator (ISG).

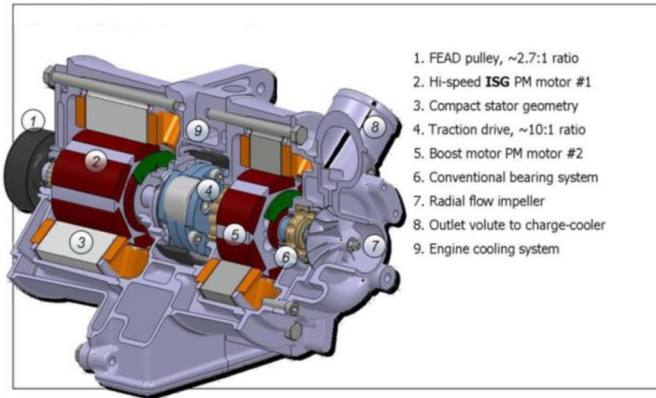


Fig. 2. SuperGen system cutaway

A high voltage DC bus connects both motor controllers to a small high voltage energy store. A DC-DC converter is also used to allow energy to be sent from the SuperGen device to the vehicle low-voltage electrical systems.

Inserting a clutch between the two PM machines allows their capability to be used to provide stop-start, and electrical boost and recuperation for mild hybridization. Typically, the combined power of the two machines is of the order of 8 kW, with the split between the two not having to be equal so that PM machine number 1 can be configured for use solely as the alternator, meaning that SuperGen can take its place on the engine accessory drive system.

Principle of Power-Split System Functionality

The power delivery to the compressor sun gear can be achieved simultaneously by both pure mechanical means and by transferring power between E1 and E2 (in either direction). This enables full control over the compressor speed while typically requiring only 20% of the electrical power of an equivalent electrically-driven sole boosting device (or 'e-booster').

Figures 3 and 4 show that the power-split system enables the compressor speed to be continuously and accurately matched to boosting requirements of an engine without the need for clutches, recirculation or throttle valves. Figure 3 shows approximate power flows (and associated losses) via the mechanical and electrical paths through the machine, and Figure 4 shows the relationship between engine speed (and by extension E1 speed, related by the input pulley ratio), E2 speed and compressor speed. When no boost is required, parasitic losses are low since the complete traction drive and compressor rotate at pulley speed.

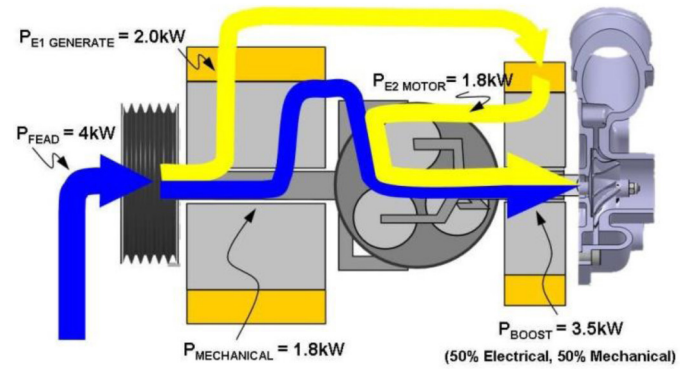


Fig. 3. Power-split electro-mechanical transmission system

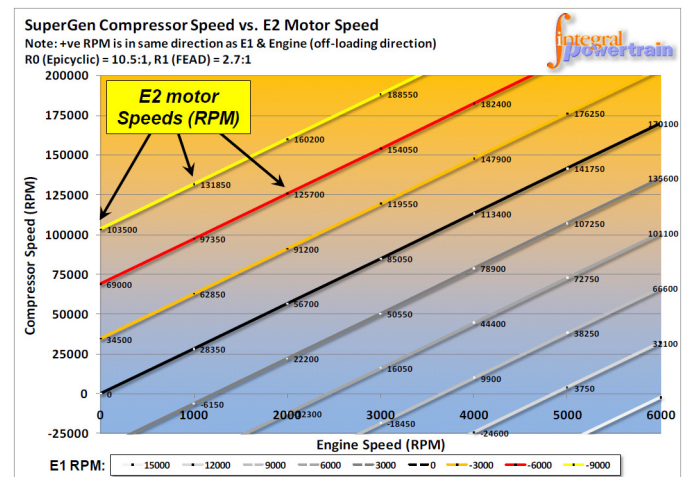


Fig. 4. Typical compressor speed map for SuperGen device, relating E1 and E2 speeds to engine rpm for a typical FEAD pulley ratio of 2.7:1. Positive values of E2 speed are in the same direction of rotation as the engine crankshaft

Boost Control Philosophy

In the transient work conducted here, boost is controlled for SuperGen by demanding a plenum pressure and using the device to make up the difference between this and what the turbocharger can supply. This is achieved by varying the speed of the impeller. Under these conditions the bypass is shut. If the turbocharger can supply the demanded boost then the bypass is opened and SuperGen is idled. The variable-ratio characteristic means that this control system can be used across the entire engine speed and load range and so provide seamless blending of the two pressure-charging stages.

MODIFICATIONS TO THE ULTRABOOST ENGINE TO FIT SUPERGEN

The baseline build for comparison was the final one reached during the Ultra Boost for Economy programme, known as the UB200 build level [1]. Figure 5 shows views of the assembled engine in which the charging system components described in Table 1 can be discerned (except for the test-cell mounted first-stage chargecooler).

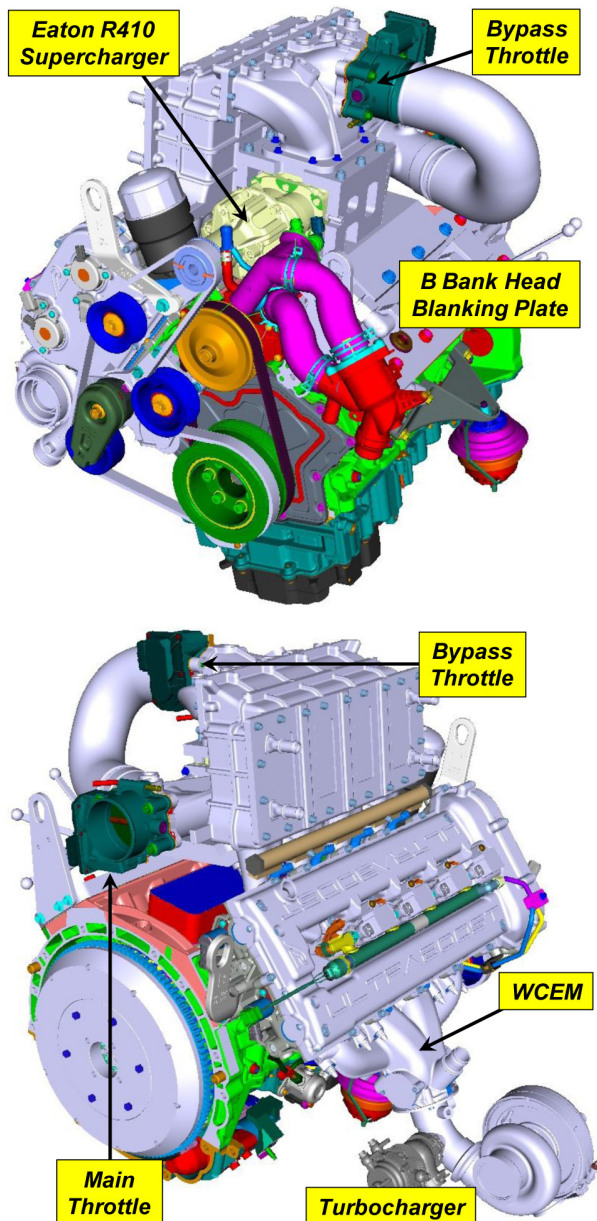


Fig. 5. CAD images of front (top) and rear (bottom) three-quarters of the Ultraboost engine in the UB200 specification used as a baseline configuration in this work

Discernible in the top side of Figure 5 are the water-cooled exhaust manifold (WCEM), Honeywell GT30 turbocharger (with its separate wastegate), and plenum chamber with integrated water-cooled second-stage chargecooler, plus the main load control throttle at the entry to the supercharger. The pipework from the turbocharger compressor outlet via the test-cell first-stage chargecooler and on to the supercharger intake throttle is not shown.

From the UB200 build level the Eaton R410 supercharger and drive belt were removed and the components necessary for mounting SuperGen added. The general configuration of the installation is illustrated in Figure 6, together with a photograph of the assembly in the test cell in Figure 7. Figure 6 shows that the belt drive had to be modified accordingly, and a Y-piece added in the air path to divide the flow after the first-stage charge cooler so that air could flow either to the SuperGen unit or around it as necessary via the bypass. It is

important to note that the air handling components replacing the standard Ultraboost UB200 parts had considerably increased volume, which must be borne in mind when considering the transient response results reported later. A schematic of the air path for the engine is shown in Figure 8; the SuperGen installation merely exchanged the Eaton with the SuperGen unit, albeit with the necessary changes to the pipework discussed above and shown in Figures 6 and 7 and with the logic of the main and bypass throttles changed.

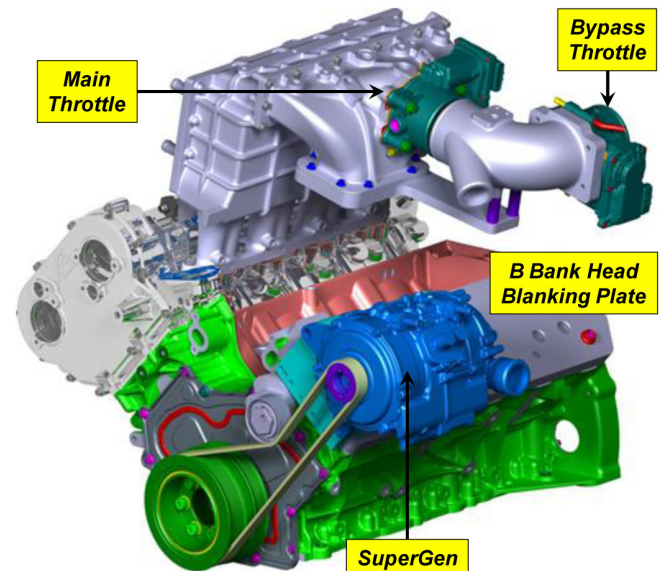


Fig. 6. SuperGen mounted to the UB200 engine. It is attached to the plate which replaced the B (or left-hand) bank cylinder head of the donor AJ133 engine. The bypass throttle is shown on the right hand side of the image; the junction through which air boosted by SuperGen passes before flowing through the main load control throttle itself is also visible (see also Figure 7)

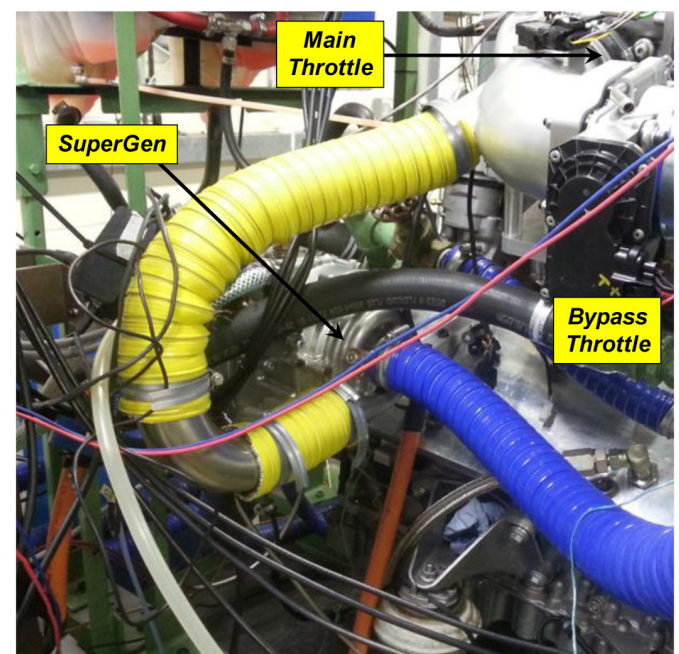


Fig.7. Photograph of the SuperGen unit installed on the Ultraboost engine. In this view, the bypass throttle is visible towards the rear of the engine and slightly above the SuperGen unit, the inlet of which has been removed from the bypass throttle. The outlet can be seen flowing back into the induction system just before the main load control throttle (see also Figure 6)