

New Compact, High Efficiency, Variable Displacement Compressor for the Small Vehicle Segment

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ABSTRACT

As fuel prices continue to rise automotive manufacturers continue to push their suppliers to provide technology that improves the potential fuel efficiency of their applications. In addition there is an increasing trend towards smaller, lighter and more compact vehicles to mitigate the automotive carbon footprint. These movements necessitated the development of a new compact, low mass, variable displacement compressor to match the requirements for these smaller and more efficient vehicles.

The new Delphi MVC, or Miniature Variable Compressor, meets these requirements by integrating the high efficiency of our latest swashplate variable compressor design into a compact and lightweight package. This design can be offered in a range of displacements from 80 to 100cc and can be offered as either internally or externally controlled to support the customer's needs.

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INTRODUCTION

The MVC was developed with both market trends and forecasts for the next several years in mind. The increasing cost of gasoline and regulations on motor vehicle pollution becoming increasingly stricter has driven auto manufacturers to smaller and more efficient products. In turn this has trickled down to the component suppliers.

As awareness of the effects of pollution on the environment has increased the consumer is also trending towards autos with smaller carbon footprints. This is most prevalent in mature markets like the TRIAD (NA, Eastern Europe, and Japan) but can also be seen in developing BRIC markets (Brazil, Russia, India, and China). Growing city population has also had an effect on vehicle size as there has been a push for more urban friendly autos.

Cognizant of these factors the MVC was created to compete in the 80 - 100 cc displacement class. This would typically be for the basic and subcompact vehicle classes. Compared to our other current Delphi offerings the MVC is smaller in both length and diameter which makes it completely unique with very few common parts. This allowed freedom to re-engineer much of the content and systematically scrutinize and optimize the design.

Enhancing the gas flow and fine-tuning manufacturing tolerances improved the efficiency. The electromagnetic clutch coil was optimized based on the new compressor displacement and latest high value features were designed into the new MVC content. FEA was done to validate the robustness and durability of the new parts.



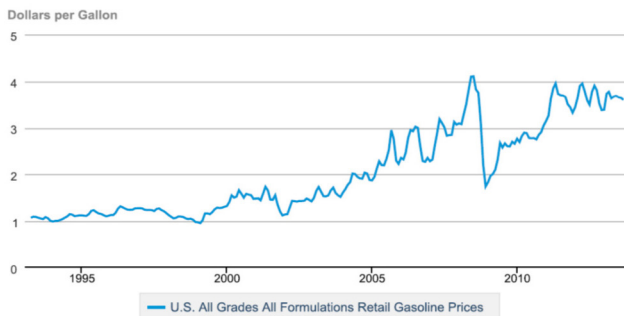
Figure 1. Delphi Miniature Variable Compressor.

RIISING FUEL PRICES AND EMISSIONS REGULATIONS

Over the last several decades gasoline fuel prices of all formulations and grades have increased globally. Reasons for the increasing prices range from economic factors to political dynamics to adverse climate and weather.

Based on data compiled by the U.S. EIA, the retail price of gasoline per gallon has more than tripled in the U.S. since 1993 (\$1.050 September 1993 to \$3.604 September 2013). [Figure 2](#) illustrates the general trend of this increase with data points being monthly average prices.

U.S. All Grades All Formulations Retail Gasoline Prices



Source: U.S. Energy Information Administration

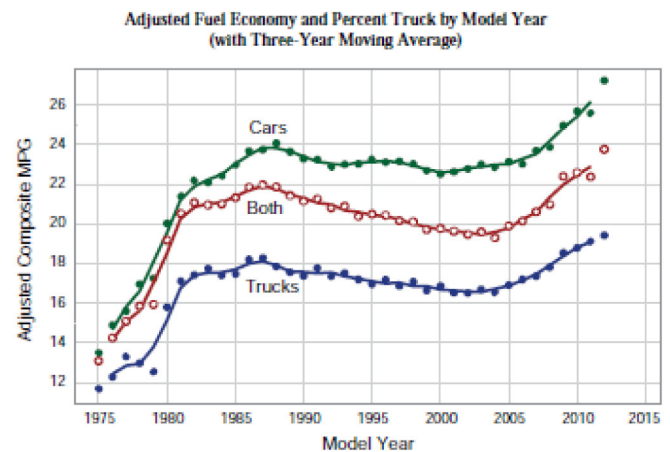
[Figure 2. U.S. retail gasoline prices of all formulations and grades.](#)
Source: U.S. Energy Information Administration.

Since the Clean Air Act Extension of 1970, which gave the EPA regulatory authority over motor vehicle emissions, the EPA has imposed the amount of pollution an automobile may emit. These restrictions have become more stringent over time as awareness of the impact pollutants have on the environment has increased.

European regulations have taken the same path. The EU (European Union) has created a progressively staged emission regulation standard which increases in severity. The latest stage, Euro 6, takes effect September 2014.

SUBSEQUENT MARKET TRENDS AND FORECASTS

Within the U.S. market there has been a shift from the consumer to purchase autos with better fuel economy. [Figure 3](#) depicts consumer auto purchases within the U.S. over the last few decades. With the largest ascension in U.S. retail gasoline prices coming between 2002 and 2008 a direct relation is realized with consumer purchases over the same span. Even as fuel price within the U.S. has leveled since 2008 the trend remains the same.



[Figure 3. Adjusted composite fuel economy for personal vehicles sold in the U.S. from 1975 to 2012.](#) Source: U.S. Environmental Protection Agency.

On a global level much of the same can be said. Based on a Global Automotive Executive Survey done in 2013 by KPMG, which surveys 200 senior executives from top automotive companies, it is forecasted that the top three largest growths in demand will come from basic, subcompact, and compact vehicle classes within the TRIAD markets by 2018. Subcompact and compact classes are also forecast to be top three in demand in BRIC markets by 2018.

From the same survey it is also believed that over the next 5 years downsizing and optimizing the ICE (internal combustion engine) offers the chief solution for increased fuel efficiency. Most believe that electric cars are still 6-10 years away in technology to overtake ICEs.

SWASHPLATE VARIABLE MECHANISM DESIGN

Several factors were evaluated in order to create a compact and lightweight compressor. The first area that was evaluated was the internal mechanism as it controls the subsequent package size of the compressor. Optimization of the mechanism enables the compressor design to be both shorter and diametrically thinner. The mechanism full stroke angle and bore circle diameter can be reduced which leads to an overall reduction in package size. These two parameters can be looked at as objective functions that need to be minimized. The design limits are summarized in [Table 1](#).

[Table 1. Upper and lower design limits.](#)

	Lower Design Limit	Upper Design Limit
Stroke Angle	Zero stroke, as no pumping would occur	Max stroke before piston shoe escape
Bore Circle Diameter	Smallest bore circle dia to maintain adequate web thickness between bores	Current 5 piston offering bore circle dia



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To establish a set of values for full stroke angle and bore circle diameter it is easiest to derive equations for both in terms of relative variables. Stroke angle and bore circle diameter greatly affect each other and thus there are tradeoffs in minimizing one versus the other. Figure 4 is a 2D layout showing the terms related to the derivation of equations for stroke angle and bore circle diameter.

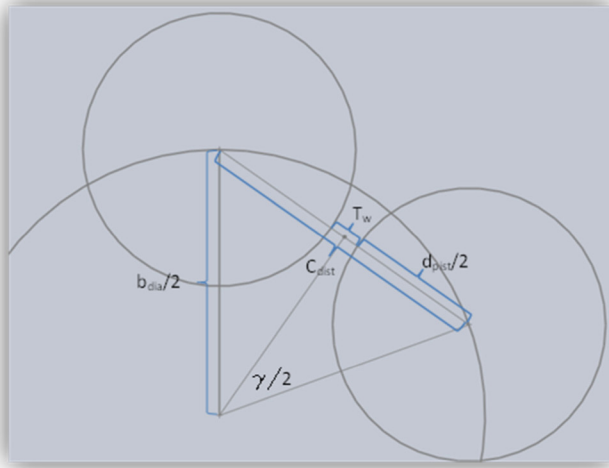


Figure 4. MVC 2D geometric layout of bore circle.

The derivation of the design formulas was done in radians and based on the fact that the combination of objectives needed to produce a displacement of 100 cc.

$$\gamma = \frac{2\pi}{n}$$

$$\sin \frac{\gamma}{2} = \frac{\frac{c_{dist}}{2}}{\frac{b_{dia}}{2}}$$

$$b_{dia} = \frac{c_{dist}}{\sin \frac{\pi}{n}}$$

$$c_{dist} = T_w + d_{pist}$$

$$b_{dia} = \frac{T_w + d_{pist}}{\sin \frac{\pi}{n}}$$

(1)

$$100cc = n * \pi * \left(\frac{d_{pist}}{2}\right)^2 * b_{dia} * \sin \theta_{stroke}$$

$$\theta_{stroke} = \sin^{-1} \left(\frac{100,000 \sin \frac{\pi}{n}}{n * \pi * \left(\frac{d_{pist}}{2}\right)^2 (T_w + d_{pist})} \right)$$

(2)

n = # of cylinders

T_w = web thickness

d_{pist} = piston diameter

γ = angle between cylinder bore centers

c_{dist} = distance to cylinder bore centers

b_{dia} = bore circle diameter

θ_{str} = stroke angle

Based on the success of the 5CVC (5 piston Compact Variable Compressor, the current smallest variable displacement compressor offering from Delphi) the decision was made to optimize the design with 5 cylinders. Equations (1) and (2) are now only in terms of web thickness and piston diameter. This allows for minimization of the bore circle diameter and full stroke angle subject to variations in two variables. The possible design solutions are plotted on Figure 5. The optimal solution lies on the theoretical Pareto frontier shown. Solutions on the Pareto frontier are optimal because no improvement can be made to one objective without trading off to the other objective.

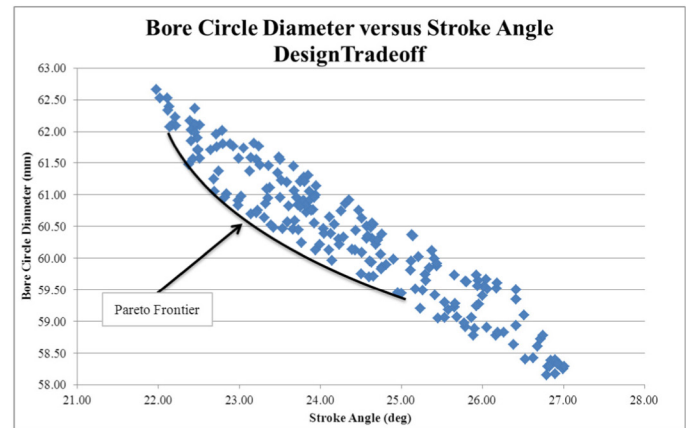


Figure 5. Bore circle diameter versus stroke angle design points. Optimal solution lies on the Pareto frontier shown in black.

HIGH VALUE AND HIGH EFFICIENCY COMPRESSOR CONTENT

The unique set of MVC content includes the latest high value and high efficiency features. High value content is defined as economical cost without loss of design robustness. The new swashplate variable mechanism was designed based on the optimized bore circle and full stroke angle. The valving was created using the latest high efficiency center flow design. Figure 6 and 7 are images depicting the new content.