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ABSTRACT

Both evaporative emissions and tailpipe emissions have been reduced by more than 90% from uncontrolled levels in state-of-the-art. However, now that the objective is to reach near-zero emission levels, the need for aggressive purging of the canister and fuel tank and the need for extremely precise control of engine Air/Fuel ratio (A/F) come into conflict. On-board diagnostics and the wide variation in operating conditions and fuel properties in the "real world" add to the challenge of resolving these conflicting requirements.

An advanced canister purge algorithm has been developed which substantially eliminates the effect of canister purge on A/F control by estimating and compensating for the fuel and air introduced by the purge system.

This paper describes the objectives and function of this algorithm and the validation of its performance. It discusses the value of a "systems solution" - matching software to a robust set of evaporative system components rather than using additional sensors and actuators for new fuel control and diagnostic functions.

INTRODUCTION

Electronic control of canister purge was widely adopted in the mid-1980s to allow a better compromise between evaporative and tailpipe emission control and driveability. In these systems, purge effects were compensated by closed loop feedback (using the exhaust oxygen sensor).

The adoption in the USA of "enhanced evap" and on-board refueling vapor recovery (ORVR), and the LEV and ULEV tailpipe standards have increased the difficulty of adequately fulfilling conflicting regulatory requirements. Furthermore, the demand for flawless driveability in all ambient conditions and with all commercial fuels, and new requirements for functional self-diagnosis with OBD II have added to the challenge in developing next generation purge systems.

Table 1. Conflicting Purge System Requirements

Function / Objective
Evaporative emission control
Enhanced EVAP
- Purge more to maintain working capacity.
- Use high purge duty cycle ramp rates.
ORVR
- Purge aggressively after refueling events.
Running Loss
- Purge aggressively in high tank T conditions.
- Use a high idle purge rate.
future: ULEV II / SULEV
- Purge more, to approach zero evap. emissions
Ultralow tailpipe emission control
LEV / ULEV fuel control
- Purge less, especially low airflow and transients.
- Use low ramp purge duty cycle rates.
- Keep purge somewhat proportional to airflow.
- Disable purge periodically to learn base fuel.
future: ULEV II / SULEV
- Purge less, avoid maldistribution due to purge
OBD II diagnostics
0.020" leak diagnostic
- Ramp purge rapidly up and down during test.
- Use very high peak purge rates.
- Inhibit purge during parts of test
interaction with other diags.
- Inhibit or disable purge during some tests: AIR, fuel trim, catalyst etc. (to avoid higher S/N, false pass, false fails)
Driveability
hot weather purge effects
- Purge less, especially low airflow and transients
fuel odor / running loss
- Purge more, stop low priority inhibits/disables
Idle quality / fuel injector specs
- Purge less to improve fuel precision at idle.

Why a new purge algorithm?

A system supplier must bring value to its OEM customers by delivering more function with less hardware.

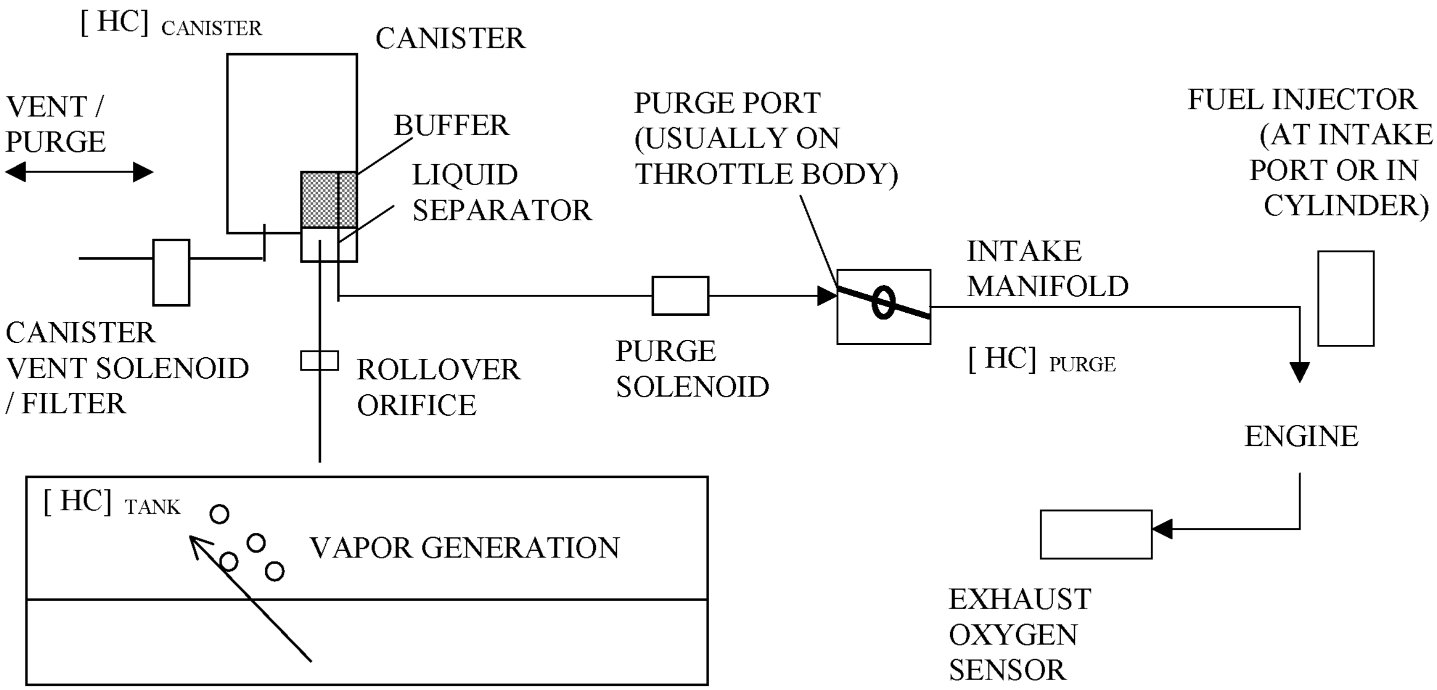


Figure 1. Typical arrangement of evaporative parts for a USA / OBD II system

The patent pending enhanced purge algorithm described in this paper seeks to have the same advantages as in the system proposed by Folkerts et al. [reference 2] without the added hardware. This is achieved by estimation of the purge fuel rate and feed-forward correction of injector pulse width.

Purge Massflow is estimated based on a physical model as a function of known temperatures, pressures, operating frequency and commanded duty cycle. Then the HC concentration is estimated based on closed loop fuel control feedback. Because this concentration changes relatively slowly with time, a reasonably accurate instantaneous fuel contribution supplied by purge can be calculated. This allows global, feed-forward compensation of the desired engine fueling net of the purge contribution.

Higher purge volume and more rapid changes in Purge duty cycle are required to meet the model year 2000 requirements (ORVR, 0.020” leak check diagnostic etc.). The intent of the algorithm is to allow these higher purge rates and to eliminate purge from producing any deterioration in fuel control or driveability.

KEY FEATURES OF THE ALGORITHM

EVAP MANAGER – A group of software processes manage the purge functions by establishing a hierarchy of priority for the various system modes. Safety always has the top priority. Diagnostics usually have the next priority (although diagnostics may be disabled in extreme conditions based on physical criteria – such as the need to purge more during very high tank temperature and pressure operation). Background functions such as learning base fuel often have high priority (but only during limited periods over a drive cycle). Similarly, this may be disabled in extreme conditions.

While this type of priority is always inherent in state based software; the grouping of these functions in the Evap Manager allows a more visible compromise between separate calibration functions. This can lead to improved system performance especially in “real world” conditions (which can otherwise be lost in the maze of Evap, tailpipe, OBD II and validation requirements).

VIRTUAL [HC] SENSOR – Figure 1 shows a typical schematic for a low emission Evap system. The purge solenoid can be increasingly seen as a significant source of metered fuel to the engine on the emissions drive cycle and in “real world” hot weather conditions.

For reference, we noted that 8% of the total engine fuel over a US FTP test came from the purge system for a test vehicle platform used in the development of this algorithm.

Unlike gasoline injectors, which meter liquid fuel of relatively constant composition, purge solenoids meter gaseous fuel of highly varying compositions (from pure ambient air to very rich fuel tank vapors, which in some conditions contain no air - only light hydrocarbons). To complicate matters further, purge is normal metered at, or close to, the throttle. Purge vapors must mix with intake air and be swept through the intake manifold before reaching the cylinders.

The objective of the virtual [HC] sensor is to estimate the fraction of engine fuel supplied by purge for each combustion event. This involves model estimation of purge massflow and adaptive learning of purge concentration. Together, these can be used to calculate the purge fuel rate at the throttle. Then this is transport delayed and filtered to estimate the purge fuel rate at the intake ports, on a real time basis.

In many respects, this is superior to a physical [HC] sensor. It estimates purge at the ports, where a physical sensor could not conveniently be located. It is feedback based – so it quickly self corrects in failure modes. Most importantly, it requires only engineering application cost and some minor upgrades of other EMS components (as discussed later in the paper). Therefore, the cost per unit can be very low compared to a hardware intensive solution.

PURGE MASSFLOW MODEL – The Pneumatic State Estimator / Thermal State Estimator (PSE/TSE) software uses thrifted physical plant models to estimate engine flows, pressures and temperatures [reference 1]. This approach has also been applied to the purge system, allowing an estimate of purge mass flow without the use of added sensors. Two versions of this massflow estimate have been developed:

1. a stand-alone version (for customers who purchase a purge subsystem).
2. an integrated version (for “system” customers who have adopted the PSE/TSE framework as the core of their EMS product).

In both cases, the purge massflow is estimated with similar logic based on measured and estimated variables and control parameters. This is shown schematically in Figure 2. This uses the normal structure used in the PSE/TSE for massflow through pneumatic valves. Standard massflow is represented in tabular form vs. pressure ratio (Pressure_2 / Pressure_1) and geometry. In this case, the geometry term is the variable effective area, defined by Purge duty cycle. Other variables, such as Temperature, Density and Voltage can be used to adjust for second order effects and correct to actual ambient conditions from standard.

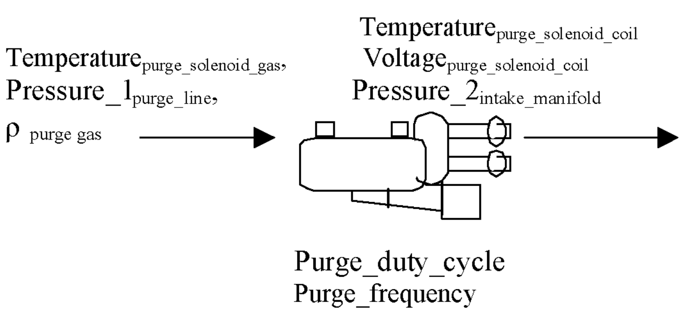


Figure 2. Primary variables and control parameters used to estimate Purge Massflow

ADAPTIVELY LEARNED HC CONCENTRATION – As previously discussed, the HC concentration of either the gas drawn through the canister or the gas purged from the tank vapor space is unknown at the start of any given trip. Many sources of variation exist which cause the closed loop fuel logic to trim fuel rates up and down. But purge is the largest source of variation and one which is under direct control. The second largest source of variation is often PCV vapors, which are usually metered with a passive system – and thus show up as gradual shift in the base fuel trim. By periodically learning the base fuel with purge off, shifts in engine fueling with purge on can be reasonably attributed to purge. While base fuel can be logically corrected with multiplicative corrections learned into speed / load ranges, the independent variable that needs to be learned for purge is HC concentration [HC]. This is trimmed to a “best estimate” by learning up or down until any shift is fueling with purge on is canceled out. This is an iterative calculation based on closed loop fuel control feedback, where the fuel contribution supplied by purge (ϕ_{PURGE}) is calculated according to the following formula:

$$\varphi_{PURGE} = \frac{(\text{Purge Massflow* [HC]* Air Fuel Ratio})}{\text{Engine Airflow}} \tag{1}$$

The HC concentration changes relatively slowly, especially when a buffered canister is used (described later in the hardware discussion). Therefore, the fraction of engine fuel supplied by purge can be estimated on a feed forward basis, by continuously calculating this fraction as the other variables change rapidly. This is represented as a gas carburetor, where a fraction of the needed engine fuel is pre-mixed with air at the throttle as shown in Figure 3.

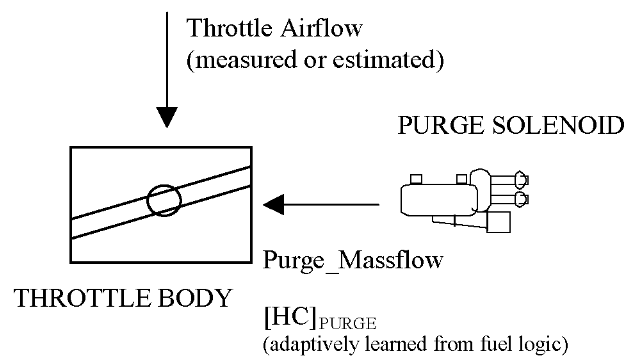


Figure 3. Variables used in the calculation of ϕ_{PURGE} (at the throttle)

Thus purge must be filtered and transport delayed to estimate the purge fraction at the port. To be more precise, equation (1) should use a throttle airflow estimate or corrected airmeter reading in the denominator – as this is the point where the purge gas is metered. This transport delay and filtering is shown (schematically) in Figure 4, for the case of a transition from purge ON to purge OFF.

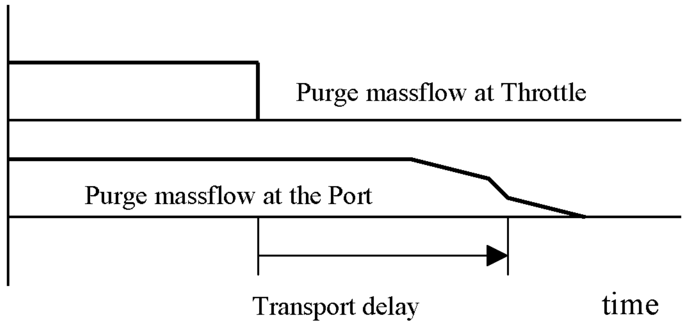


Figure 4. Transport delay and filtering of ϕ_{PURGE} across the intake manifold

VALIDATION OF ALGORITHM PERFORMANCE

EMISSION RESULTS – A series of emission tests were run on 3.2L V6 light duty truck development vehicle. This vehicle had a 100 K mile laboratory aged catalytic converter and achieved approximately the LDT2 LEV1 emission level with indolene fuel. A summary of the tests is shown in Table 2, which compares emissions performance with and without purge.

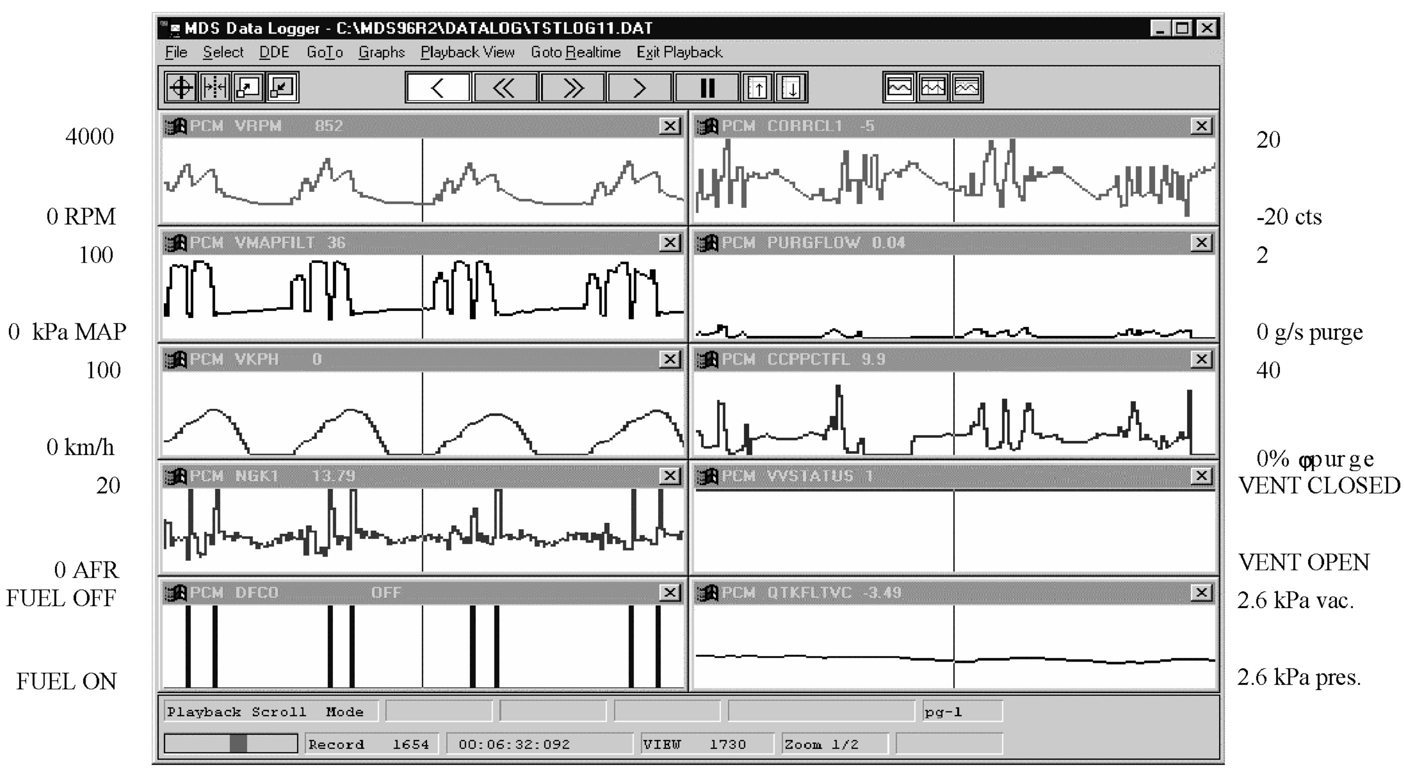
There is a small change in emissions – reflective of a slight bias in the lean direction. It is believed that this could be eliminated with further optimization of exhaust gas recirculation (EGR) and closed loop calibration to give more or less identical emissions with or without a saturated canister. It is notable that CO emissions were lower with the saturated canister tests. Higher CO is normally an indicator of deteriorated fuel control due to purge.

Table 2. Emission results summary for 3.2L Forward EMS development vehicle

V6 – Average of 2 tests	NMHC	CO	NOx	FE	Purge Vol.	Mass Purged
	Emissions(wtd. g/mi)			MPG	(L/test)	(g/test)
Saturated canister	0.131	1.23	0.198	16.22	358	80.70
No purge	0.142	1.42	0.177	15.87	0	0

PHOENIX CITY TRAFFIC CONDITIONS – Perhaps more important than the FTP test results, the hot weather performance of the algorithm was tested with simulated city traffic drive cycles at mid ambient temperature (25 - 30 °C) using 15 Reid vapor pressure (RVP).

Datalog 1 shows a graphical output of a test using Delphi's modular development system (MDS) datalogger tool. This shows 10 variables vs. time (Engine speed, Manifold Absolute Pressure (MAP) Vehicle Speed, Measure A/F ratio, Deceleration Fuel Cut-Off (DFCO) status, Closed Loop Fuel Correction in counts, Purge Massflow estimate, ϕpurge estimate, Canister vent solenoid (CVS) status and Tank Vacuum (scaled from pressure to vacuum).



Datalog 1. Phoenix city traffic fuel control, 2.4L test car (15 RVP fuel, 25 °C ambient)

Note that the vehicle had a 5 speed manual transmission, and the use of DFCO during gearshifts is apparent.

While the C/L logic clearly has to chase significant errors, driveability was observed to be identical with purge on and off. Although data is not presented here, we did run some buffered vs. non-buffered canister tests and found that the closed loop fuel control signatures were more stable in the case of the buffered canister. Thus the buffered canister is useful for some applications, such as:

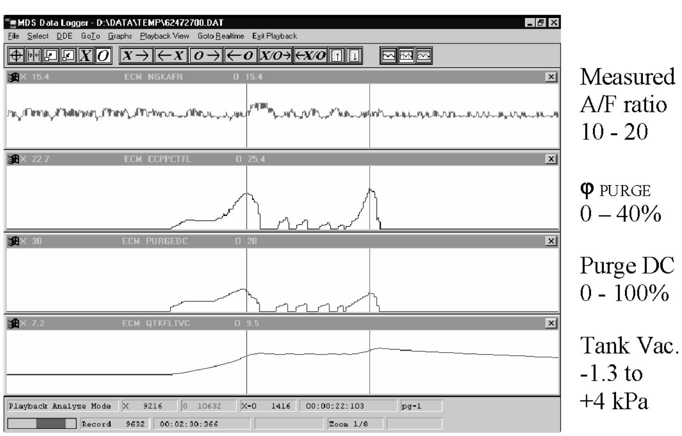
- severe applications with hot running fuel tanks and/or high performance engines.
- new applications targeted at ULEV 2 and near-zero evaporative emissions levels.
- premium applications (where perfect fuel control and flawless hot weather driveability are firm requirements).

Note the component discussion, later in the paper.

Note also that the canister vent solenoid is closed throughout the test. Another patent pending feature in the advance purge algorithm is an active running loss control strategy. This prevents vapors from being released even in severe, low speed conditions where fuel can start to boil in the tank. In these conditions, the instantaneous vapor generation rate may exceed the engine's capacity to consume them. The increase in tank pressure suppresses the vapor generation, allowing the contained vapors to be consumed or recondensed later in the trip.

EVAP LEAK CHECK DIAGNOSTIC – As previously discussed, OBDII diagnostic tests required rapid variation in purge duty cycle when drawing vacuum in the tank and evaluating for any leak in the system. Datalog 2 shows the compensation for fuel from purge during a development test with 13 RVP fuel. While fuel contribution from purge supplies as much as 28% of the engine fuel, the measured A/F trace shows a maximum error of about 8%.

Of course, this is a very severe case and fuel control with normal volatility fuels is much better.



Datalog 2. Fuel control during 0.020" evap leak test at idle with 13 RVP fuel

SUBTLETIES OF APPLICATION

While the basic function of the advanced canister purge algorithm is relatively simple (once taught), there are many subtleties of application which make the virtual [HC] sensor more accurate, or which avoid problems related to other sources of fuel variation.

Recall that this is an inferential measurement and, as such, it is not intended to be accurate to +/- 1% of engine fuel in extreme transient conditions. It is intended to be accurate within 5% in all operating conditions. This represents a large improvement from errors with traditional purge logic, which would exceed 25% (for equally aggressive calibrations) for example, during a 0.020" leak diagnostic at idle. There were significant issues which had to be resolved in order to reach this level of performance, particularly related to the closed loop fuel logic and calibration. Furthermore, as a virtual [HC] sensor, the accuracy depends very significantly on good hardware. This drives tighter requirements for several of the evap system and other EMS components – especially the purge solenoid, canister and fuel injectors.

COMPONENT REQUIREMENTS

Of course, the virtual [HC] sensor function estimates the hydrocarbon concentration without an actual sensor. But the precision of the estimate is highly dependent on other evaporative and fuel sub-system components and also on control software. As a system supplier, Delphi is able to design and integrate the key components and control software to achieve the desired precision.

A discussion of the key components and their requirements (for accuracy of the [HC] estimate) follows:

PURGE SOLENOID – In order to estimate accurately the fuel contribution from purge, it is essential that the purge solenoid be repeatable over the operating temperature, voltage and pressure ratio range. Whenever the purge solenoid massflow is relatively linear (vs. duty cycle) and repeatable, the estimate of fuel contribution from purge will be sufficiently accurate and fuel control, emissions and driveability will be significantly improved. But if the purge solenoid mass flow is erratic or non-linear, then the predictive power of the algorithm goes away and fuel control regresses to that of conventional purge logic (or worse).

The best way around these potential problems is to design a more robust and repeatable purge solenoid. Delphi's family of enhanced precision purge (EPP) solenoids has several industry leading features which give superior performance in hot weather, low voltage and low vacuum conditions.

The EPP solenoid has been designed to operate in a wider range of temperatures. To give repeatable performance at 125 °C, it has an optimized magnetic path – that gives consistent opening response and thus linearity and repeatability at low duty cycles (critical in the idle area). Even in applications that do not normally run this hot, the EPP design gives an extra margin of performance that will extend reliability and repeatability under low voltage and high vacuum conditions and reduce the statistical variability across a set of parts. It has a long stroke and internal geometry that make it resistant to particle contamination (and versions with internal filtration are also available).

The variability in slope and opening response of the purge solenoid is the primary factor in defining the accuracy of the fuel correction for purge from the virtual [HC] sensor system.

CANISTER – While the canister effects on the system are more subtle, several features of Delphi's enhanced evap and ORVR canisters also make them especially well suited to the best performance of the virtual [HC] sensor. Firstly, the canister should be low restriction. Secondly, the canister should have a large and effective liquid trap to avoid "slugs" of liquid fuel reaching the engine and to prevent a significant shift in perceived concentration vs. purge massflow. Thirdly, Delphi has developed a second generation buffer system to damp the variation in HC concentration as the canister vent solenoid is opened and closed, and as vapor generation from the tank varies.

Figure 5 shows the port arrangement and buffer cross-section of Delphi new buffered on-board refuelling vapor recovery (ORVR) canister design.

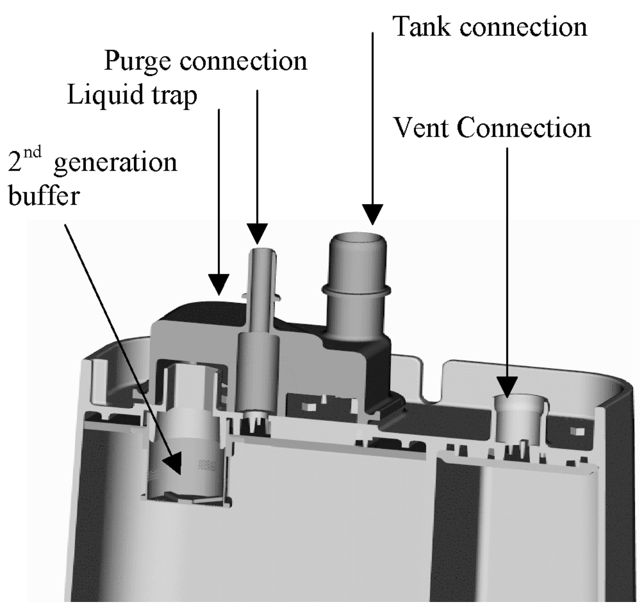


Figure 5. Cross-section of a Delphi ORVR canister (with 2nd generation buffer system)

The advanced purge algorithm has been developed to work adequately with non-buffered canisters, using separate RAM variables for tank and canister HC concentrations. However, it adds more complexity to the logic to maintain acceptable levels of fuel control when cycling the canister vent solenoid (CVS). To reach the lowest emission levels and have perfect purge fuel control (and hence driveability), the new buffer system shows clear benefits.

FUEL INJECTORS – In the spirit of the zero and near-zero evap requirements for California, future purge systems will have to be capable of much higher purge rates at idle. This is particularly true for the OBD II 0.020" leak test. In this context, fuel injector linearity and repeatability at low pulse widths becomes a key injector performance characteristic. Delphi's Multec 2 mini fuel injector has significantly improved dynamic range compared to previous injector generations and competitive parts. This determines the minimum precisely deliverable fuel quantity. Figure 6 shows the minimum deliverable pulse for Delphi's Multec 2 injector compared to three competitive parts (with similar static flow).

Note that the minimum pulse is much lower than a typical idle injected fuel quantity of > 5 mg. This allows the flexibility to purge aggressively at idle and still have accurate liquid injection in conditions where purge supplies a large fraction of engine fuel.

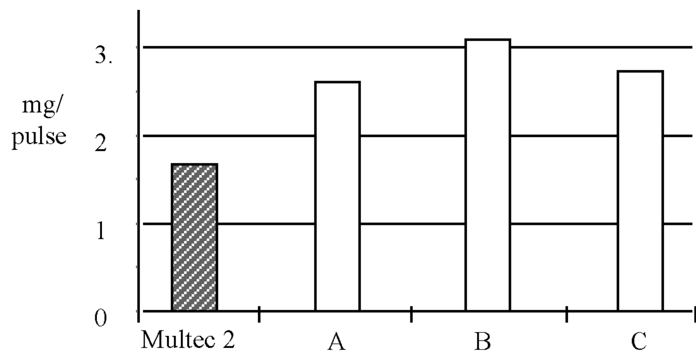


Figure 6. Minimum repeatable injected fuel quantity of benchmarked port fuel injectors

OTHER COMPONENTS – Of course, to some extent all of the EMS fuel and air metering components sensor (ACV, EGR, PCV, camshaft, lifters and valves etc.) have some effect on the purge system and thus on the accuracy of the virtual [HC] sensor. This is another example of why increased system performance at the lowest system cost cannot be achieved by sourcing with a component focus. It is also a justification for the PSE/TSE software foundation, as variation in one element of the system can be evaluated analytically and dynamically simulated – and so the system interactions can be more rigorously assessed and linked.

CONTROL SOFTWARE

Closed loop logic and fuel calibration – In addition to having ideal component designs (in the features described), it is necessary that the base fuel control be developed in a way that makes the virtual [HC] sensor as accurate and repeatable as possible. Traditionally, closed loop fuel control operation has allowed a relatively immature open loop fuel calibration to achieve reasonable emission performance.

At current and future very low emission levels, the open loop fuel calibration must be much more accurate. With an automated and systematic calibration process, this accuracy can be achieved and we do not anticipate that the virtual [HC] sensor system puts any additional constraints on an optimal open and closed loop fuel calibration.

CONCLUSIONS

1. An advanced purge control algorithm has been developed which contains a virtual [HC] sensor. It has been shown to offer improved fuel control and evaporative sub-system performance without added hardware.
2. The linkage of component, subsytem and system requirements that is evident in the application of this strategy show the added value of a system approach.
3. As we move into the future, complexity and sophistication of EMS software will explode. Physically based control software, rigorous automated development processes and tools and an optimal mix of physical and virtual sensors will be needed to deal with this complexity and to achieve improved system performance and lower system cost.

ACKNOWLEDGMENTS

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CONTACT

Please contact the authors by e-mail:

edward.g.himes@delphiauto.com

m.james.grieve@delphiauto.com

UNITS

Metric units have been generally used in this paper (as is our practice in EMS development). However US / English units are used in referring to specific emission and diagnostic standards of the US EPA and CARB.

Specifically:

g/mile = 0.625 g/km

0.020” (or 20 thousands of an inch) = 0.51 mm

US gallon = 3.79 L

Other acronyms in the paper are defined as follows:

EMS: Engine Management System
S/N: signal to noise ratio
[HC]: hydrocarbon concentration in percent (0% is pure air, 100% is pure fuel vapors)
MPG: miles / US gallon
RPM: engine revolutions / min.
AFR: air to fuel ratio (by mass)
cts: counts (fuel pulse width closed loop correction in controller I/O clock counts)
ACV: Air Control Valve (or electronic throttle)
EGR: Exhaust Gas Recirculation
PCV: Positive Crankcase Ventilation
RAM: Random Access Memory