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Mark H. Svoboda
Delphi Automotive Systems

ABSTRACT

When an air meter is specified for an engine management system, air meter accuracy is given high priority. Air meter manufacturers characterize the accuracy of their products using laboratory instrumentation to measure the air meter output vs. flow characteristics. Ultimately the air meter is applied to an engine management system in a vehicle. The engine management system must use the information provided by the air meter without the benefit of laboratory instrumentation. Therefore, the entire measurement system must be considered in evaluating the effective accuracy. The most fundamental aspect to consider is the output signal format between the air meter and the engine management system. Two commonly available formats will be investigated: frequency and voltage.

This paper develops the equations relating signal resolution and accuracy to such factors as air meter flow curve shape, air flow dynamic range, analog-to-digital converter resolution, frequency range, timer period resolution, and measurement strategy. These equations will allow evaluation of the uncertainty introduced by the measurement system for both voltage-out and frequency-out air meters. Airflow measurement under steady state conditions is examined for both signal formats. Using the equations developed here, one can compare the tradeoffs in measurement accuracy of various air meter interface approaches for specific situations.

INTRODUCTION

Air meters are used to provide a real-time measurement of the airflow into an engine, so that the engine management system can schedule the appropriate amount of fuel for the current engine speed and load conditions. A common technique for measuring airflow rate is to use some form of hot-wire anemometry. A heated element is maintained at a controlled temperature rise above ambient temperature. This heated element is exposed to the air flowing into the engine so that the air draws heat away from the heated element. The amount of power that is required to maintain the temperature of the heated element, and hence the voltage across the heater, varies with the flow rate. The voltage across the heater can be scaled to provide an output that varies with flow.

The air rate information measured by the air meter must be communicated to the engine management system. Current commercially available air meters provide this information either as an analog voltage or as a frequency-modulated signal. A block diagram of a voltage-out air meter system is presented in Figure 1. The voltage developed internally across the heater, which varies nonlinearly with flow, is fed to an amplifier. The gain and offset of the amplifier are calibrated to provide a specified output voltage vs. flow characteristic for the air meter. The voltage signal out of the air meter is fed to an Analog to Digital (A/D) converter in the engine controller. The engine controller converts this voltage to flow information using a lookup table based on the known voltage vs. flow characteristic of the air meter.

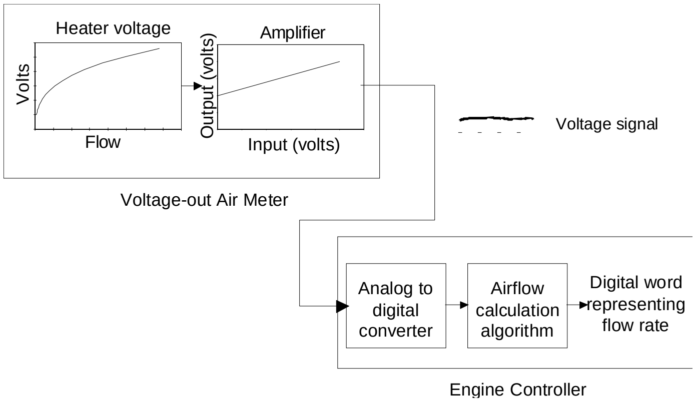

Figure 1. Block diagram of voltage-out air meter system

A frequency-out air meter system is similar. The heater voltage, which varies nonlinearly with flow, is fed to a voltage-controlled oscillator. The oscillator is calibrated to provide a specified output frequency vs. flow characteristic for the air meter assembly. The output signal, which is in this case a frequency, is fed to a timer-input circuit in the engine controller. The air meter frequency pulses are processed and converted to flow rate information based on the known frequency vs. flow characteristic of the air meter. A block diagram of a frequency-out air meter system is given in Figure 2.

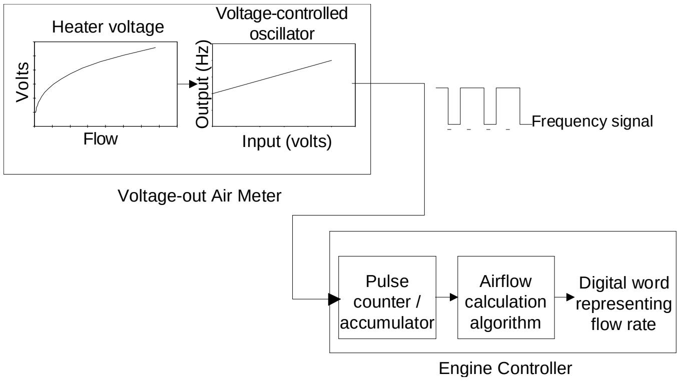

Figure 2. Block diagram of frequency-out air meter system

Each of these implementations of an air measurement system has its own considerations that influence the ultimate accuracy of the measurement. Both voltage-based and frequency-based systems will be examined, with a typical air meter characteristic curve, so that the real world behavior can be evaluated.

For the discussion that follows, it will be assumed that the air meter does not contribute any error to the measurement. The air meter itself will be treated as if it provides a perfectly characterized output for any given flow. This is not strictly true, since any mass-produced component has some tolerance associated with it. However, the instrumentation used to measure the air meter during its manufacture and calibration can be expected to have tighter tolerances than the corresponding components in the engine controller.

Measurement system errors will be evaluated as factors that cause a difference between the flow information represented in the air meter output and the digital word representing flow rate within the engine controller. In the case of a voltage-out air meter system, these factors include such things as A/D converter resolution, voltage reference accuracy, and sample rate. A frequency-based interface is influenced by time base resolution and accuracy, as well as the algorithm used to read the air meter output. Additionally, an air meter system can be affected by electrical noise and flow noise, regardless of whether the interface is voltage-based or frequency-based.

Several sample calculations are presented in this paper to show how the equations derived here can be used to evaluate a measurement system. It should be noted that the measurement system parameters used in these examples (such as A/D converter resolution, sample rates, etc.) are chosen for illustrative purposes only. These numbers do not represent capabilities of any specific engine management system, and are not intended as recommendations for system implementation.

MATHEMATICAL DESCRIPTION OF AIR METER CHARACTERISTICS

Consider an air meter which operates based on the principle of hot-wire anemometry as describe above. Several automotive component manufacturers currently produce variations of this type of air meter. Figure 3 shows a typical output curve for a production air meter produced by Delphi Automotive Systems.

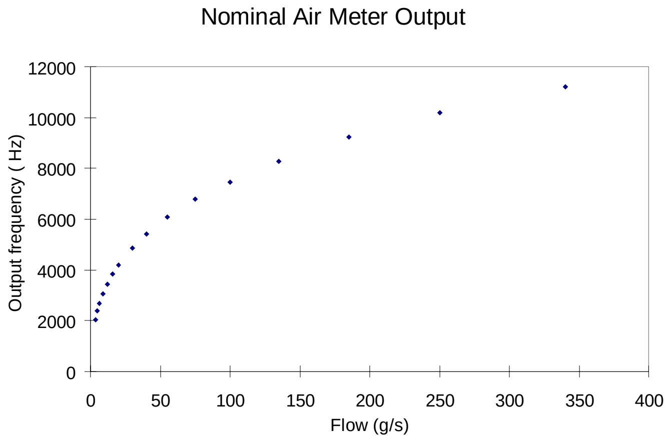

Figure 3. Published output vs. flow characteristic

The curvature seen here is typical of any manufacturer's hot-wire or hot-film air meter, whether its output is presented as a voltage or as a frequency. The amplifier in a voltage-out air meter, or the voltage-controlled oscillator in a frequency-out air meter, applies a straight-line gain and offset to the raw sensing bridge voltage. In either case, the basic curve shape is the same.

For the analysis that follows, it is useful to develop an equation that represents the relationship between flow and air meter output. Based on King's Law, the characteristic curve of a hot-wire or hot-film air meter can be modeled as:

$$output = a + b * flow^{c} \tag{1}$$

Modeling the air meter output in this form has several advantages:

1. This form has a theoretical basis (King's Law).
2. The modeled function agrees well with measured air meter characteristics.
3. The modeled function does not have inflection points that may be present if a high-order polynomial is used to fit the data.
4. The derivative is well behaved and easily calculated.

In Equation 1, *a* and *b* represent calibration parameters used to scale the output (frequency or voltage) to the desired output range, while the exponent *c* describes the curvature inherent in any hot-wire or hot-film air meter. Using least squares curve fitting to determine the coefficients in Equation 1 to match the air meter characteristic shown in Figure 3, the best fit is obtained with a = -1147, b = 2190, and c = 0.297. Therefore, this air meter output characteristic can be described as:

$$frequency = -1147 + 2190 * flow^{0.297} \tag{2}$$

Figure 4 shows the modeled characteristic as a solid line, compared to the measured output plotted as discrete points. Unless otherwise noted, this characteristic will be used in this paper to represent the air meter in a frequency-based measurement system.

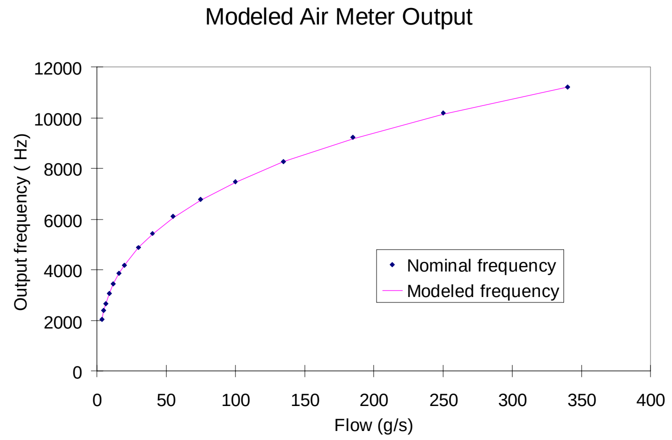

Figure 4. Modeled vs. measured air meter characteristics

As mentioned earlier, the exponent c is a function of the fundamental air meter design, while the offset a and the gain b are calibration factors used by the manufacturer to obtain the desired output range for the required flow range. Equation 1 can be used at the maximum and minimum flows to determine values of a and b to mathematically fit the curve to any output range (frequency or voltage). Thus, we have:

$$output_{\min} = a + b * flow_{\min}^{\ c} \tag{3}$$

$$output_{\max} = a + b * flow_{\max}^{\ c} \tag{4}$$

Subtracting Equation 3 from Equation 4 and rearranging, we can solve for b, obtaining:

$$b = \frac{output_{\max} - output_{\min}}{flow_{\max}^{\ c} - flow_{\min}^{\ c}} \tag{5}$$

Substituting for b in Equation 3 and rearranging, we obtain:

$$a = output_{\min} - \frac{output_{\max} - output_{\min}}{flow_{\max}^{\ c} - flow_{\min}^{\ c}} flow_{\min}^{\ c} \tag{6}$$

Define R as the dynamic range in flow over the desired output span, where $flow_{\max}$ is the flow at the maximum desired output and $flow_{\min}$ is the flow at the minimum desired output.

$$R = \frac{flow_{\max}}{flow_{\min}} \tag{7}$$

The offset and gain can be represented in terms of the flow dynamic range as

$$a = \frac{R^c output_{\min} - output_{\max}}{R^c - 1} \tag{8}$$

$$b = \frac{output_{\max} - output_{\min}}{(R^c - 1)\, flow_{\min}^{\ c}} \tag{9}$$

MODELING A VOLTAGE-OUTPUT AIR METER – Knowing the desired output range (frequency or voltage) and the required flow range, simulated calibration constants can thus be obtained to allow modeling of the air meter flow curve. For example, consider an air meter designed to span 0 to 5 volts for a flow range of 3.5 to 340 g/s. (This flow range is chosen for this example merely to match the specified flow range of the commercial frequency-out air meter depicted in Figure 3. Different gain and offset calibrations in the air meter amplifier or voltage-controlled oscillator circuit can accommodate engines with different low flow or high flow requirements.)

Assume the characteristic flow curve has an exponent c equal to 0.297. For this case,

$$R = \frac{340}{3.5} = 97.14$$

$$R^c = 97.14^{0.297} = 3.893$$

$$a = \frac{(3.893)(0) - 5}{3.893 - 1} = -1.728$$

$$b = \frac{5 - 0}{(3.893 - 1)(3.5)^{0.297}} = 1.191$$

Therefore, a voltage-output air meter as described above can be modeled using the equation:

$$output = -1.728 + 1.191 * flow^{0.297} \tag{10}$$

The characteristic curve described by Equation 10 is shown graphically in Figure 5. This air meter characteristic will be used in the analysis of a voltage-out air meter system that follows.

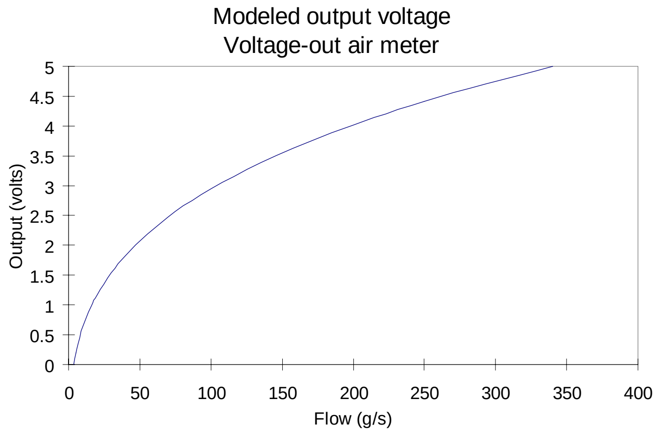

Figure 5. Modeled voltage-out air meter characteristics

RELATING AIR METER OUTPUT VARIATION TO FLOW VARIATION

Consider the typical use of an air meter in an engine management system. Airflow rate is measured, so that fuel injection can be scheduled to maintain the desired air/fuel ratio. Errors in airflow determination, expressed as a percentage of reading, correspond directly to percentage error in air/fuel ratio. Therefore, when discussing air meter accuracy, it is appropriate to speak in terms of percentage of the quantity of flow being read. Examining the flow curves presented earlier, two things become obvious:

1. A given change in output (voltage or frequency) corresponds to a different change in flow depending on where you are operating on the flow curve. This is due to the fact that the slope decreases as the flow increases.
2. A given change in flow (g/s) represents a different percentage of reading depending on where you are operating on the flow curve.

Because of these two factors, changes in the measured output must be converted to the corresponding percentage change in indicated flow at the particular flow point.

A small change in flow will cause a change in the air meter output that depends on the slope of the output vs. flow curve at the particular flow point.

$$\Delta output\,(volts) = \Delta flow\left(\frac{g}{s}\right) * slope\left(\frac{volts}{(g/s)}\right) \tag{11}$$

(The units for the air meter output are given as volts in Equation 11, which is appropriate for a voltage-out air meter. In the case of a frequency-out system, Hertz would be substituted for volts, and the slope would be in units of Hz/(g/s).)

The change in indicated flow corresponding to a change in air meter output is determined by rearranging Equation 11.

$$\Delta flow = \frac{\Delta output}{slope} \tag{12}$$

To express output change as percent of flow reading, we divide the flow deviation by the nominal flow, and multiply the result by 100%.

$$\begin{aligned}\Delta\%\, flow &= \frac{\Delta flow}{flow} * 100\% \\ &= \frac{\Delta output}{slope * flow} * 100\%\end{aligned} \tag{13}$$

Equation 13 gives the general relationship between change in air meter output and percentage change in indicated flow. In order to use this relationship, the slope of the output vs. flow curve must be known at the flow point of interest. In actual practice, this slope is usually estimated by using an interpolation algorithm on actual measured data to predict what the output would be at flows just above and just below the flow point of interest. The slope is then estimated by dividing the difference in calculated output by the difference in flow values used to generate the interpolated output values. For this paper, due to the nature of the modeled air meter characteristic, the slope of the modeled output vs. flow curve can be evaluated directly at any flow.

The slope of the modeled output vs. flow curve can be calculated by taking the derivative of Equation 1.

$$\begin{aligned}slope &= \frac{d\ output}{d\ flow} \\ &= \frac{d}{d\ flow}\left(a + b * flow^{c}\right) \\ &= bc * flow^{c-1}\end{aligned} \tag{14}$$

Substituting Equation 14 into Equation 13 gives

$$\begin{aligned}\Delta\%\, flow &= \frac{\Delta output}{(bc * flow^{c-1}) * flow} * 100\% \\ &= \frac{\Delta output}{bc * flow^{c}} * 100\%\end{aligned} \tag{15}$$

RESOLUTION OF A VOLTAGE-OUT AIR METER SYSTEM

The resolution of a measurement system can be expressed as the amount the input must change before a change can be recognize at the output. An engine management system that incorporates a voltage-out air meter will read the air meter signal using an analog to digital (A/D) converter. An *n*-bit A/D converter divides the input voltage range into 2^n steps. For example, an 8-bit A/D converter can resolve 2^8, or 256 distinct voltage ranges, while a 10-bit A/D converter can resolve 2^{10}, or 1024 voltage ranges. Therefore, the voltage resolution of an *n*-bit A/D converter is described as:

$$resolution = \frac{input_{\max} - input_{\min}}{2^n counts} \tag{16}$$

Typically, the input range of an A/D converter is 0 to 5 volts. Thus, if an 8-bit A/D converter is used, each A/D count represents a voltage resolved to (5 volts)/256, or 19.5 millivolts. A 10-bit A/D converter can resolve (5 volts)/1024, or 4.88 millivolts.

Consider a system that uses a 10-bit A/D converter to measure the air meter signal. For this example, we will use the voltage-out characteristic curve developed earlier, as described by Equation 10 and illustrated in Equation 5, namely:

$$output = -1.728 + 1.191 * flow^{0.297}$$

These coefficients give a 0 to 5 volt output for flows ranging from 3.5 to 340 g/s. At 3.5 g/s, the output is 0 volts. As the flow increases, the voltage will increase, but the A/D converter output will not increment until the flow has changed enough to cause the voltage to exceed 4.88 millivolts.

Equation 1 can be rearranged to find the flow that will produce a given output, as:

$$flow = \left(\frac{output - a}{b} \right)^{1/c} \tag{17}$$

Evaluating Equation 17 to find the flow that produces an output of 4.88 mv, we find that the A/D converter will increment at a flow of 3.5346 g/s. Thus, any flow between 3.5 g/s and 3.5346 g/s will give the same A/D converter output reading. The resolution, expressed as percent of reading, under these conditions, is:

$$\frac{3.5346 - 3.5}{3.5} * 100\% = 0.99\% \tag{18}$$

Therefore, for a voltage-out air meter system as described, with a 10-bit A/D converter, the flow measurement resolution at low flow is 0.99% of reading.

To derive a general expression for measurement system resolution, the expression for A/D converter resolution given in Equation 16 can be substituted for Δ*output* in Equation 15. This yields:

$$\Delta\%\, flow = \frac{input_{\max} - input_{\min}}{2^n bc * flow^c} * 100\% \tag{19}$$

In order to maximize the useable resolution of the measurement system, the air meter should be specified such that the output spans the entire available A/D converter input range. Since the air meter output span appears in the determination of the air meter gain coefficient *b* (see Equation 9), and setting the air meter output range equal to the A/D converter input range, Equation 19 can be rewritten as:

$$\Delta\%\, flow = \frac{(R^c - 1)\, flow_{\min}{}^c}{2^n c * flow^c} * 100\% \tag{20}$$

where *R* is the flow dynamic range over the output range as defined in Equation 7.

Using this equation to calculate the resolution of our modeled voltage-out air meter with a 10-bit A/D converter at 3.5 g/s, we get:

$$\Delta\%\, flow = \frac{\left[\left(\frac{340}{3.5} \right)^{0.297} - 1 \right] (3.5)^{0.297}}{2^{10} (0.297) * 3.5^{0.297}} * 100\%$$

$$= 0.951\% \tag{21}$$

This value agrees well with the value calculated in Equation 18.

Equation 20 can be used to evaluate the resolution of a voltage-out air meter under a variety of conditions. The following sections will examine the effects of A/D converter resolution, flow dynamic range, and air meter curve linearity individually.

EFFECT OF A/D CONVERTER RESOLUTION ON A VOLTAGE-OUT AIR METER SYSTEM – Assume an air meter with a characteristic curve as described by Equation 10. Such an air meter has an exponent *c*=0.297, calibrated to span 3.5 to 340 g/s (dynamic range *R*=97.14), Table 1 gives the resolution in percent of flow reading for various flows and various A/D converter resolutions.

Table 1. Effect of A/D converter resolution

Resolution (% of flow reading)			
Flow (g/s)	**A/D converter resolution (bits)**		
	8	9	10
3.5	3.80%	1.90%	0.95%
10	2.79%	1.39%	0.70%
25	2.12%	1.06%	0.53%
50	1.73%	0.86%	0.43%
100	1.41%	0.70%	0.35%
200	1.14%	0.57%	0.29%
340	0.98%	0.49%	0.24%

Obviously, at any given flow rate, the resolution improves by a factor of 2 for each additional bit of A/D converter resolution. This table also illustrates another important fact. For a typical air meter curve shape, the resolution of a voltage-out air meter is worst at low flow rates and improves with increasing flow. This is more easily seen when these results are graphed, as shown below in Figure 6.

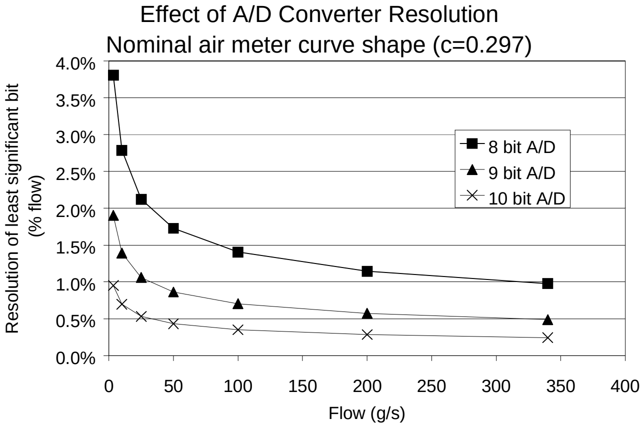

Figure 6. Effect of A/D Converter Resolution

EFFECT OF FLOW DYNAMIC RANGE ON A VOLTAGE-OUT AIR METER SYSTEM – The dynamic range *R*, defined as the flow corresponding to the maximum output value divided by the flow at the minimum output value, appears in Equation 20. Table 2 examines the effect of flow dynamic range on the output. This table assumes an 8 bit A/D converter, with air meter curvature corresponding to an exponent *c*=0.297. Three different air meter calibrations are assumed, corresponding to flow ranges typical of different engine displacements. These calibrations are defined such that the indicated calibration flow range spans the 0 to 5 volt output range. For purposes of this illustration, the following 3 calibrations are assumed:

- 0 volts at 3.5 g/s, 5 volts at 150 g/s
- 0 volts at 3.5 g/s, 5 volts at 250 g/s
- 0 volts at 3.5 g/s, 5 volts at 340 g/s

Table 2. Effect of flow dynamic range on a voltage-out air meter system

Resolution (% of flow reading)			
Flow (g/s)	**Calibration flow range (g/s)**		
	3.5 to 150	3.5 to 250	3.5 to 340
3.5	2.70%	3.36%	3.80%
10	1.98%	2.46%	2.79%
25	1.51%	1.87%	2.12%
50	1.23%	1.52%	1.73%
100	1.00%	1.24%	1.41%
200	N/A	1.01%	1.14%
340	N/A	N/A	0.98%

These results are presented graphically in Figure 7.

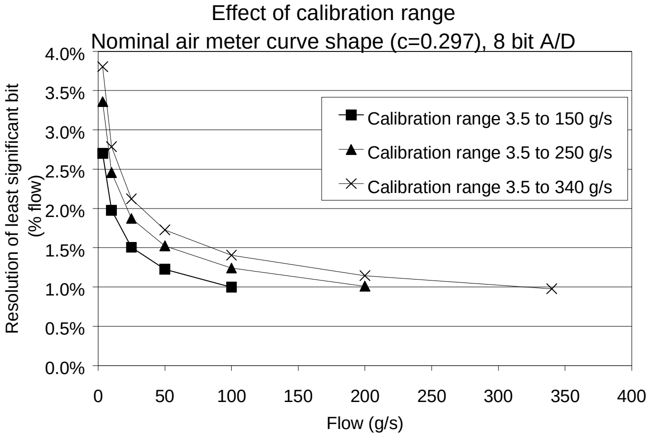

Figure 7. Effect of calibration flow range on resolution of frequency-out air meter

To interpret the results shown in Table 2 and Figure 7, consider a flow of 25 g/s. If the air meter is calibrated to span 3.5 to 150 g/s over the 0 to 5 volt output range, the resolution at 25 g/s will be 1.51% of reading. The same flow, measured with an air meter calibrated to span 3.5 to 340 g/s over the same output range, can be read with 2.12% resolution. Therefore, with a voltage-out air meter, care should be taken to match the air meter calibration to the actual engine airflow range. Using an air meter that is able to read flows beyond what will be encountered on the engine results in degraded resolution at the flows which will actually be encountered.

EFFECT OF AIR METER LINEARITY ON A VOLTAGE-OUT AIR METER SYSTEM – The above examples all assume an air meter characteristic curve which is typical of a hot-wire or hot-film air meter, namely, a characteristic that can be modeled as $a+b*flow^{0.297}$. It is possible to make an air meter with a straight-line relationship between flow and output. This could theoretically be implemented by using a nonlinear amplifier to linearize the raw voltage from the hot-wire. In addition, alternative approaches to airflow measurement could conceivably produce such a characteristic output curve.

A straight-line characteristic would be described mathematically as *output=a+b*flow*. For the same flow and voltage ranges we have considered in previous examples (0 to 5 volts out corresponding to flows from 3.5 to 340 g/s), the equation describing this relationship would be

$$output = -0.052 + 0.01486 * flow \qquad (22)$$

Figure 8 illustrates this relationship graphically.

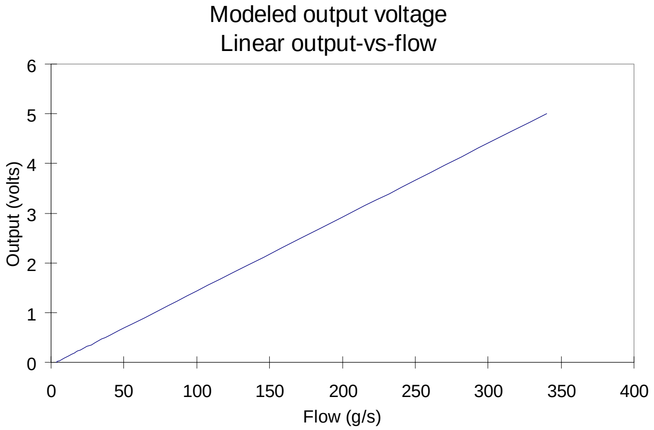

Figure 8. Modeled linear voltage-out air meter

Note that this characteristic corresponds to a value for the exponent *c*=1 in Equation 1. Using Equation 20, with the exponent *c*=1, the resolution of an air meter with linear output can be calculated as presented in Table 3.

Table 3. Resolution of a linear-output air meter

Flow (g/s)	**A/D converter resolution (bits)**		
	8	9	10
3.5	37.56%	18.78%	9.39%
10	13.14%	6.57%	3.29%
25	5.26%	2.63%	1.31%
50	2.63%	1.31%	0.66%
100	1.31%	0.66%	0.33%
200	0.66%	0.33%	0.16%
340	0.39%	0.19%	0.10%

To confirm these calculations, consider a 10-bit A/D converter at a flow of 3.5 g/s. According to Equation 22, the output will be 0 volts at 3.5 g/s. The output reaches 4.88 mv (the first transition of a 10-bit A/D converter) at a flow of 3.827 g/s, which is 9.4% higher than 3.5 g/s. Thus, there is a 9.4% flow range that gives the same A/D converter output value. This agrees with the value indicated in Table 3.

Again, it is easier to visualize these results if they are charted. The resolution of 8, 9, and 10 bit A/D converters when used to measure a linear output-vs.-flow air meter is graphed in Figure 9.

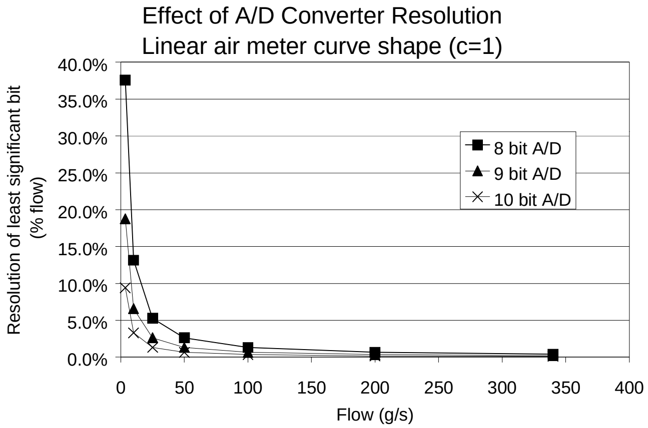

Figure 9. Effect of A/D converter resolution with linear curve shape

Compare the values in Table 3 and Figure 9 (linear output-vs. -flow) to the values obtained earlier in Table 1 and Figure 6 (typical hot-wire curve shape). It can be seen that the low flow resolution is severely degraded with a linear output characteristic. At the high end of the flow range, the linear characteristic offers some improvement in resolution compared to the typical hot-wire curve. In reality, this offers no advantage. As pointed out earlier, with a typical hot-wire curve shape, low flow resolution is already worse than high flow resolution. Because air-fuel control at low flow is most critical in terms of factors such as emission compliance and idle quality, linearizing the output is a step in the wrong direction.

It can be shown that increasing the curvature, by letting the exponent *c* approach zero, results in equal percentage flow change per volt, regardless of flow. Further increases in curvature, obtained mathematically with negative values for the exponent *c*, result in further improvement in low-flow resolution at the expense of high-flow resolution. While this is easy to do mathematically, the cost of implementing this distortion in actual air meter hardware seems to outweigh any marginal benefit that may be obtained.

RESOLUTION OF A FREQUENCY-OUT AIR METER SYSTEM

To discuss the resolution of a frequency-out air meter system, one must consider how a frequency is actually read. Frequency is defined as events per unit time, and in a laboratory frequency counter, transitions of the input signal are counted over a fixed time interval. To improve the resolution of the frequency measurement, the time interval can be increased.

While this approach may be fine in a laboratory, it is not useable in an engine management system. In a vehicle, information about airflow rate must be available with minimal delay, to allow proper scheduling of fuel delivery. Therefore, an engine management system will determine the output of a frequency-out air meter based on the period, or time between corresponding transitions, of the air meter signal. The resolution of this system will depend on the ability of the measurement system to resolve time increments.

For example, consider the Delphi frequency-out air meter discussed earlier. Recall that the equation describing this air meter (Equation 2) is

$$frequency = -1147 + 2190 * flow^{0.297}$$

At a flow of 3.5 g/s, the frequency is 2030.11 Hz, which corresponds to a period of 492.34 microseconds. Assume that the engine management system can resolve period to the nearest microsecond. Consider the effect of 1 microsecond resolution for this air meter, at this flow condition. With 1 microsecond resolution, the period that is read will be either 492 microseconds or 493 microseconds. At a period of 492 microseconds, the frequency is 2032.52 Hz, which corresponds to a flow of 3.5089 g/s (using Equation 17). Similarly, 493 microseconds is 2028.40 Hz, corresponding to 3.4937 g/s. The difference between these results, expressed as percentage of flow, is

$$\frac{3.5089 - 3.4937}{3.5} * 100\% = 0.434\% \tag{23}$$

Thus, a 1 microsecond resolution for this air meter at 3.5 g/s results in a measurement resolution of 0.434% of flow reading.

It is useful to develop a general expression relating change in measured period to percentage change in indicated flow. Consider the model of an air meter developed earlier (Equation 1). For a frequency-out air meter, this becomes:

$$frequency = a + b * flow^{c} \tag{24}$$

Because it is period and not frequency that is actually being measured, take the reciprocal of Equation 24 to calculate the period as a function of flow.

$$T = \frac{1}{frequency} = \frac{1}{a + b * flow^{c}} \tag{25}$$

The change in period per change in flow is obtained by taking the derivative of Equation 25.

$$\frac{dT}{d\ flow} = \frac{-bc * flow^{c-1}}{(a + b * flow^{c})^{2}} \tag{26}$$

The reciprocal of Equation 26 gives the change in indicated flow per change in period.

$$\frac{d\ flow}{dT} = -\frac{(a + b * flow^{c})^{2}}{bc * flow^{c-1}} \tag{27}$$

Assuming that for small changes, the differential can be replaced by the difference, the change in indicated flow corresponding to a change in measured period is given as

$$\Delta flow = -\Delta T \frac{(a + b * flow^{c})^{2}}{bc * flow^{c-1}} \tag{28}$$

To determine the percentage change in indicated flow that corresponds to a change in period, divide Equation 28 by flow and multiply by 100%.

$$\begin{aligned} \Delta\%\ flow &= \frac{\Delta flow}{flow} * 100\% \\ &= -\Delta T \frac{\left(a + b * flow^{c}\right)^{2}}{\left(bc * flow^{c-1}\right) * flow} * 100\% \\ &= -\Delta T * \frac{\left(a + b * flow^{c}\right)^{2}}{bc * flow^{c}} * 100\% \end{aligned} \tag{29}$$

To verify Equation 29, consider again the effect at 3.5 g/s of a 1-microsecond change in period for the frequency-out air meter described by the equation

$$frequency = -1147 + 2190 * flow^{0.297}$$

Per Equation 29,

$$\begin{aligned} \Delta\%\ flow &= -(1 * 10^{-6}) \frac{\left(-1147 + 2190 * 3.5^{0.297}\right)^{2}}{2190 * 0.297 * 3.5^{0.297}} * 100\% \\ &= -0.437\% \end{aligned}$$

The negative sign in this result indicates that as period increases, indicated flow decreases because the frequency of the output signal decreases. The calculated magnitude compares well with the 0.434% obtained in Equation 23.

Equation 29 can be used to calculate the percentage of flow associated with timer resolution for this modeled air meter at different flow rates, assuming measurement is being made over a single period of the air meter signal. These results, for timer resolutions of 1, 5 and 10 microseconds, are shown in Table 4 and in Figure 10.

Table 4. Effect of timer resolution

Resolution (% of flow reading) Single-period measurement			
Flow (g/s)	**Timer resolution (msec)**		
	1	5	10
3.5	0.437%	2.184%	4.368%
10	0.791%	3.954%	7.908%
25	1.223%	6.117%	12.235%
50	1.647%	8.237%	16.475%
100	2.174%	10.872%	21.744%
200	2.827%	14.133%	28.266%
340	3.428%	17.138%	34.277%

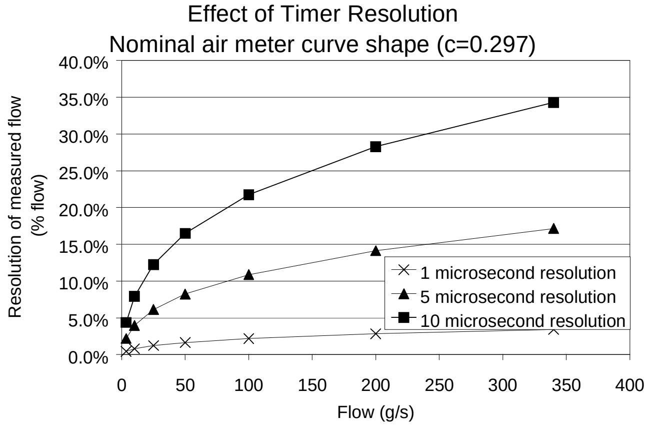

Figure 10. Effect of timer resolution with nominal curve shape

Table 4 and Figure 10 illustrate the resolution if calculations are made at each transition of the air meter frequency signal. This results in poor resolution at high flow rates. Also, such a technique would place a significant burden on the engine controller if it was required to do all necessary calculations and table look-ups every air meter period. For these reasons, it is more reasonable to accumulate information on air meter frequency events, and only do the translation to flow less often. The determination of airflow rate can be done based on time (one calculation per some number of milliseconds) or based on engine events (one calculation per some number of degrees of crank angle). A suitable algorithm for either case is described next.

FREQUENCY-OUT AIR METER WITH PULSE ACCUMULATION – The algorithm described here calculates the air meter signal frequency based on an integer number of air meter pulses. To do this, it is necessary to be able to increment a pulse counter each time the air meter signal goes through a transition in a given direction (either high-to-low or low-to-high). In addition, it is necessary to be able to capture the value of a free-running timer when the proper transition occurs. Assuming the transition of the air meter signal generates an interrupt, the handling of the air meter frequency signal interrupt would be as shown in the flow chart in Figure 11.

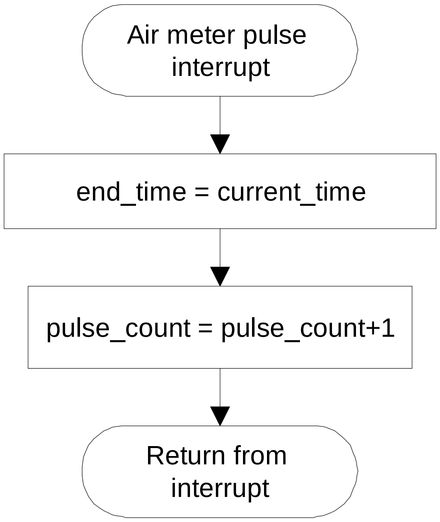

Figure 11. Flow chart of pulse-handling interrupt algorithm

The air rate can be calculated less frequently than once per air meter signal period. This calculation may be event based (for example, once per engine cylinder event) or time based (once per some number of milliseconds). When it is time to calculate the air meter frequency to update the flow information, the frequency can be determined by dividing the integer number of air meter pulses measured since the last calculation by the elapsed time represented by that number of pulses. This routine must also reinitialize the memory locations used by the pulse interrupt handler for time accumulation and pulse count accumulation. A flow chart of a suitable calculation routine is presented in Figure 12.

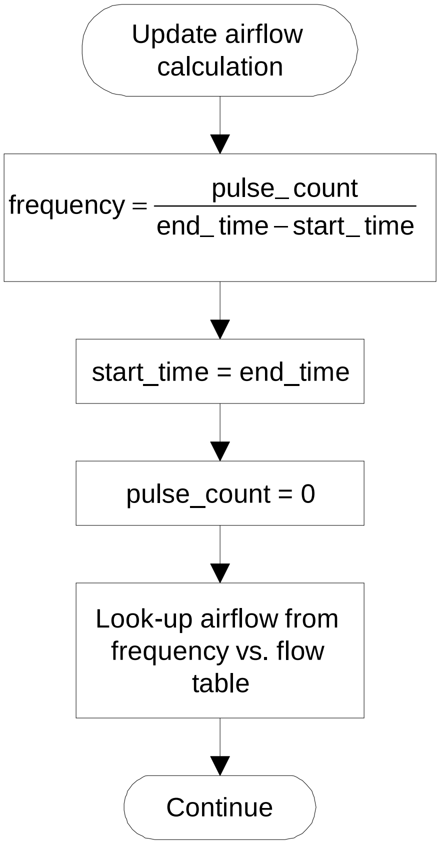

Figure 12. Flow chart of airflow calculation algorithm

A timing diagram illustrating this algorithm is presented in Figure 13. The top waveform indicates the times at which the calculation occurs, and the bottom waveform indicates the air meter frequency signal. For the purpose of this illustration, assume the high-to-low transitions of the air meter signal are used to trigger the interrupt handling routine described in Figure 11. The pulse count is incremented on each falling edge of the air meter signal. When a calculation is performed, it is based on an integer number of air meter signal periods. For example, in the illustration, the n^{th} calculation uses the 3 air meter output periods that were completed since the previous calculation. The calculation routine resets the pulse count. Obviously, provisions must be made to handle the situation where the air meter transition and the calculation update occur nearly simultaneously.

The air meter frequency signal is asynchronous relative to the calculation interval. Due to the uncertainty in the relative phasing of the air meter frequency relative to the calculation interval, the number of air meter pulses used in the calculation may vary by one, even with no variation in either air meter frequency or sample interval. This is illustrated in Figure 13, where the number of air meter pulses per calculation interval can be either 3 or 4.

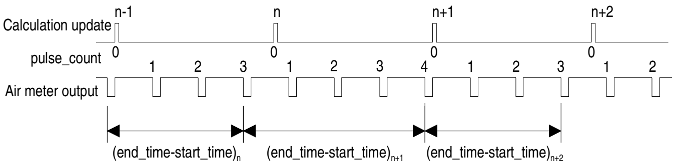

Figure 13. Timing diagram for frequency-out air meter algorithm

By accumulating a number of air meter pulses, the effect of timer resolution is effectively divided by the number of air meter pulses used in the calculation. For example, if 2 pulses are accumulated with 10-microsecond timer resolution, this is essentially the same as if one pulse was measured with 5-microsecond timer resolution. As pointed out above, the number of air meter transitions used in a calculation can vary by one under steady state conditions. The worst case resolution occurs when the lower number of air meter transitions is used in the analysis. The number of air meter transitions per calculation interval is simply the product of the air meter output frequency and the calculation interval. For example, consider an air meter frequency of 2030 Hz and a calculation interval of 3 milliseconds. The number of air meter transitions per calculation interval would be:

$$(2030\ Hz)(0.003\ sec) = 6.09$$

Therefore, most calculations would use 6 air meter transitions, while 7 would be used about once every eleven calculations. Mathematically, the worst case improvement in resolution is the lower of these 2 numbers, which is the integer part of the product. For the nominal frequency-out air meter we have been considering, the minimum number of air meter pulses per calculation interval is as shown below, for calculation intervals of 3, 10, and 30 milliseconds.

Table 5. Number of accumulated air meter pulses per calculation interval

Air meter transitions per calculation				
Flow (g/s)	**Frequency (Hz)**	**Calculation interval (msec)**		
		3	**10**	**30**
3.5	2030.111	6	20	60
10	3192.544	9	31	95
25	4549.817	13	45	136
50	5852.036	17	58	175
100	7451.924	22	74	223
200	9417.526	28	94	282
340	11220.83	33	112	336

Recall from Table 4 that the resolution of a frequency-out air meter, based on single-period measurement, degrades as the flow rate increases. By accumulating multiple air meter pulses, the effective resolution improves by a factor equal to the number of pulses included in the calculation, as shown in Table 5. Because the frequency of the air meter increases with increasing flow, the improvement factor is greater at higher flow. Combining the results of these two tables, the effective resolution of a frequency-out air meter obtained by accumulating pulses over a calculation interval can be calculated by dividing the resolution in Table 4 by the improvement factor in Table 5. The results of this calculation are given in Table 6.

Table 6. Effect of timer resolution and calculation interval

Effective resolution (% of flow reading) with pulse accumulation				
Flow (g/s)	**Calculation interval (msec)**	**Timer resolution (microseconds)**		
		1	5	10
3.5	3	0.073%	0.364%	0.728%
10		0.088%	0.439%	0.879%
25		0.094%	0.471%	0.941%
50		0.097%	0.485%	0.969%
100		0.099%	0.494%	0.988%
200		0.101%	0.505%	1.010%
340		0.104%	0.519%	1.039%
3.5	10	0.022%	0.109%	0.218%
10		0.026%	0.128%	0.255%
25		0.027%	0.136%	0.272%
50		0.028%	0.142%	0.284%
100		0.029%	0.147%	0.294%
200		0.030%	0.150%	0.301%
340		0.031%	0.153%	0.306%
3.5	30	0.007%	0.036%	0.073%
10		0.008%	0.042%	0.083%
25		0.009%	0.045%	0.090%
50		0.009%	0.047%	0.094%
100		0.010%	0.049%	0.098%
200		0.010%	0.050%	0.100%
340		0.010%	0.051%	0.102%

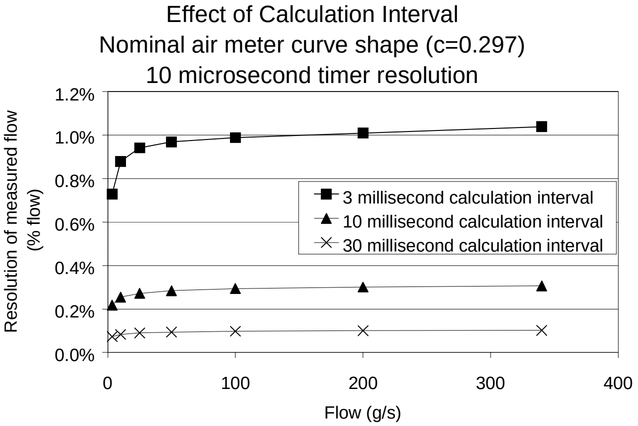

Figure 14. Resolution of frequency-out air meter with pulse accumulation

A plot of the resolution for the cases of 10 microsecond timer resolution (right-most column of Table 6) for three different values of calculation interval is given in Figure 14.

Compare Table 6 (and Figure 14) to Table 4 (and Figure 10). It is clear that an algorithm that accumulates air meter frequency output pulses before performing the frequency calculation can result in significant improvement in flow resolution, compared to a technique which considers each individual air meter output period. For the conditions evaluated, the resolution at low flow is still better than the resolution at high flow, but the imbalance is not as pronounced as it was without period accumulation. In addition, a frequency accumulation algorithm puts less computational demand on the engine controller compared to measurement of each air meter period.

EFFECT OF FLOW DYNAMIC RANGE ON A FREQUENCY-OUT AIR METER SYSTEM – In the earlier discussion of a voltage-out air meter system, a comparison was made among three different air meter calibrations, corresponding to three different engine displacements. To allow comparison between voltage-out and frequency-out systems, the same flow ranges will be examined. For purposes of this comparison, assume the frequency-out air meters are calibrated to span the range of 2030 Hz at the lowest flow to 11221 Hz at the highest flow. These frequencies correspond to the air meter modeled by Equation 2 (which is based on the characteristics of a production air meter produced by Delphi), at 3.5 and 340 g/s. Similar to the analysis done for the voltage-out system, the following calibrations will be assumed:

- 2030 Hz at 3.5 g/s, 11221 Hz at 150 g/s
- 2030 Hz at 3.5 g/s, 11221 Hz at 250 g/s
- 2030 Hz at 3.5 g/s, 11221 Hz at 340 g/s

Determining the effective resolution for these systems requires the following steps:

1. Determine the coefficients *a* and *b* that give the proper outputs at the flow extremes (assume the exponent *c* is the same for all calibrations)
2. Determine the frequency out at each flow of interest
3. Determine the effective resolution improvement factor due to pulse accumulation, at each flow, by taking the integer part of the product of the frequency and the calculation interval
4. Determine the effective resolution by calculating the raw resolution using Equation 29, and dividing by the improvement factor due to pulse accumulation.

This analysis, summarized in Table 7 and Figure 15, was done assuming a timer resolution of 10 microseconds and a calculation interval of 3 milliseconds, and an assumed air meter characteristic corresponding to the exponent *c*=0.297. Other timer resolutions and/or calculation intervals will change the absolute numbers, but the relationship between the columns will be essentially the same.

Table 7. Effect of flow dynamic range on a frequency-out air meter system

Resolution (% of flow reading) Based on 10 microsecond timer resolution, 3 millisecond calculation interval			
Flow (g/s)	**Calibration flow range (g/s)**		
	3.5 to 150	3.5 to 250	3.5 to 340
3.5	0.517%	0.642%	0.728%
10	0.673%	0.767%	0.879%
25	0.816%	0.889%	0.941%
50	0.853%	0.904%	0.969%
100	0.896%	0.962%	0.988%
200	N/A	0.981%	1.010%
340	N/A	N/A	1.039%

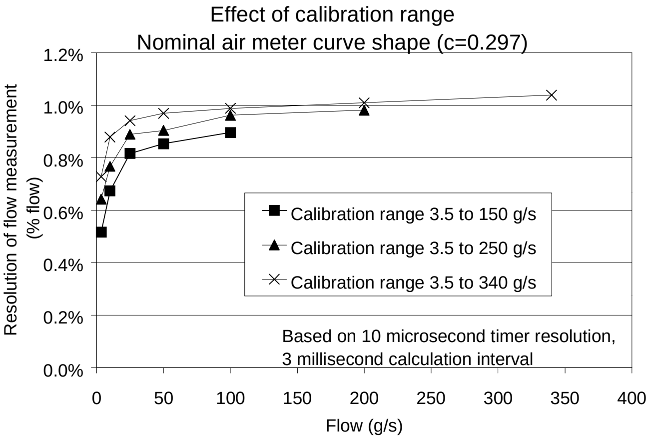

Figure 15. Effect of calibration flow range on resolution of frequency-out air meter

The results in Table 7 and Figure 15 are to be interpreted similarly to the results presented earlier for a voltage-out air meter system (see Table 2). For example, consider a flow of 25 g/s. For a frequency-out air meter calibrated to span 3.5 to 150 g/s over an output range of 2030 to 11221 Hz, the effective resolution available at 25 g/s is 0.816% of reading. The same flow can be resolved to 0.941% of reading on an air meter designed to span a flow range of 3.5 to 340 g/s for the same frequency range. Thus, the resolution is degraded at any flow if an air meter calibration is chosen which can read flows beyond the flows that may actually be encountered. Earlier, this was also shown to be true for a voltage-out air meter system. However, the degradation for the frequency-out air meter is less than that of a voltage-out air meter. If the degradation is judged to be acceptable, this may enable a customer to specify one calibration of air meter to cover two or more engine applications, thus saving costs associated with multiple part numbers. This scenario is more likely with a frequency-out air meter than with a voltage-out air meter.

EFFECT OF AIR METER LINEARITY ON A FREQUENCY-OUT AIR METER SYSTEM – Just as was done earlier with a voltage-out air meter system, the resolution of an air meter with a straight-line frequency-vs.-flow relationship can be evaluated. For the same output and flow ranges previously considered (2030 Hz at 3.5 g/s, 11221 Hz at 340 g/s), the output of such a meter would be described as:

$$\textit{frequency}=1934.4+27.314*\textit{flow}$$

Again assuming pulse accumulation with 3 millisecond calculation interval, combined with 10 microsecond timer resolution, the effective resolution of such an air meter would appear as given in Table 8 and Figure 16.

Table 8. Resolution of a linear frequency-out air meter

Resolution (% of flow reading) Based on 10 microsecond timer resolution, 3 millisecond calculation interval			
Flow (g/s)	**Frequency (Hz)**	**Improvement factor**	**Effective resolution**
3.5	2030	6	7.184%
10	2207.538	6	2.974%
25	2617.241	7	1.433%
50	3300.079	9	0.886%
100	4665.755	13	0.613%
200	7397.107	22	0.455%
340	11221	33	0.411%

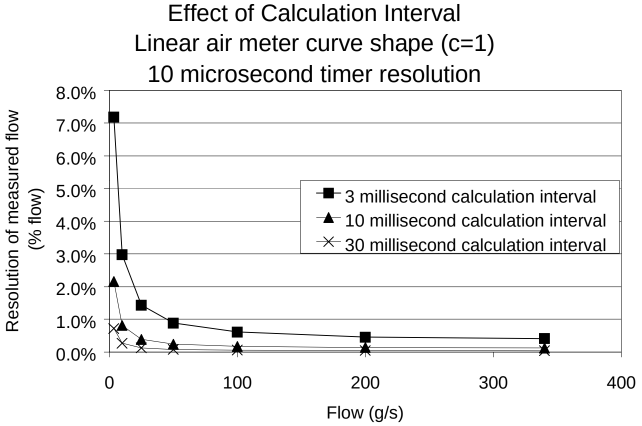

Figure 16. Effect of calculation interval with linear curve shape

Just as in the case of a voltage-out air meter (see Table 3 and Figure 9), the resolution of an air meter with a straight-line frequency-vs.-flow characteristic is unacceptably coarse at low flow rates.

OTHER SOURCES OF MEASUREMENT ERROR

The discussion thus far has concentrated on comparing the available resolution of voltage-based and frequency-based measurement systems. Other factors also influence the effective error of the measurement system. The equations developed above can be used to evaluate the percentage flow error due to other error sources in the vehicle system. Some of these other factors are discussed below.

A/D CONVERTER REFERENCE ACCURACY – An A/D converter works by comparing the input voltage to a reference voltage that is supplied to the A/D converter. The output of an n-bit A/D converter is a digital word that ranges from 0 to (2^n-1) as the input voltage ranges from 0 to the reference voltage. The ratio of the A/D reading to the full-scale A/D reading represents the ratio of the input voltage to the reference voltage. In the previous discussions on a voltage-out air meter, it was assumed that the reference voltage to the A/D converter does not contribute any inaccuracy to the measurement system.

In reality, there is some tolerance associated with the reference voltage. A voltage-out air meter will be calibrated based on instrumentation in the factory. It is safe to assume that the factory instrumentation will be certified to better accuracy than the voltage reference in the vehicle control system. If the A/D input is a voltage that is ratiometric to the reference voltage (such as the wiper of a potentiometer fed by the reference voltage), the accuracy of the A/D reference voltage is not an issue. If, however, the input to the A/D converter is presented as an absolute voltage, the tolerance on the reference voltage needs to be considered.

For small A/D reference errors, the effect of a positive percentage error on the reference is equivalent to a negative error of the same percentage on the input voltage with a perfect reference voltage. For example, if the reference voltage is one percent high (5.05 volts instead of the nominal 5 volts), the effect on the reading is the same as if the input voltage was one percent low with a perfect reference voltage. A one-percent change in output voltage will have different impacts in terms of percentage change in indicated flow depending on the flow point of interest. Recall from Equation 15, the relationship between change in output voltage and percentage change in indicated flow is given as:

$$\begin{aligned}\Delta\%\, flow &= \frac{\Delta output}{(bc * flow^{c-1}) * flow} * 100\% \\ &= \frac{\Delta output}{bc * flow^{c}} * 100\%\end{aligned}$$

For a one percent change in reference voltage,

$$\begin{aligned}\Delta output &= 0.01 * output \\ &= 0.01 * (a + b * flow^{c})\end{aligned}$$

The percentage change in indicated flow for a one-percent reference tolerance can then be calculated as:

$$\begin{aligned}\Delta\%\, flow &= \frac{\Delta output}{(bc * flow^{c-1}) * flow} * 100\% \\ &= \frac{\Delta output}{bc * flow^{c}} * 100\%\end{aligned} \tag{30}$$

Again using the modeled 3.5 to 340 g/s air meter with curvature *c*=0.297, the percentage change in indicated flow corresponding to a one-percent reference voltage error is as shown in Table 9. This assumes that the air meter is calibrated to span an absolute range of 0 to 5 volts, with perfect instrumentation used in the calibration.

Table 9. Effect of voltage reference tolerance

Percentage change in indicated flow due to 1% voltage reference change			
Flow (g/s)	**Nominal output (V)**	**Δoutput (V)**	**%flow change**
3.5	0.00	0.000	0.00
10	0.63	0.006	0.90
25	1.37	0.014	1.49
50	2.08	0.021	1.84
100	2.95	0.029	2.12
200	4.02	0.040	2.35
340	5.00	0.050	2.50

The results presented in Table 9 show that reference voltage errors result in measurement system errors that are more significant at higher flow rates. The flow change indicated in the table corresponds to a one-percent tolerance on the A/D reference voltage, and should be scaled accordingly for different tolerances.

Providing a ratiometric interface between the air meter and the A/D converter can theoretically eliminate the error corresponding to A/D converter reference error. To achieve this, the A/D reference voltage is fed to the air meter, and the air meter scales its output based on the value of reference voltage it receives. There are several drawbacks to this approach.

- A hot-wire or hot-film air meter does not inherently work on a ratiometric principle. Significant circuitry is required to scale the output of such an air meter to be ratiometric to an external reference voltage, adding to the cost of the air meter.
- A ratiometric interface requires that the A/D reference voltage be provided to the air meter. This means that an extra wire is required to interface to the air meter. The wiring harness gets more expensive, and the electrical connector gets larger, possibly impacting the ability to package the air meter underhood.

- Extending the voltage reference to the air meter increases the chance that damage to wiring insulation could result in the reference voltage line being shorted to an undesirable point. System failure mode analysis must ensure that such an occurrence will not adversely affect engine operation or cause damage to other sensors that depend on the reference voltage.

TIME BASE ACCURACY – Just as voltage reference accuracy is an issue for a non-ratiometric voltage-out air meter, time base accuracy is an issue for a frequency-out air meter. Again, it is safe to assume that the error in the instrumentation used in the factory to calibrate the air meter is negligible compared to the variability in the population of engine controllers used in the field. Time base inaccuracy could be due to factors such as part-to-part variability, component aging, or temperature sensitivity of the frequency-determining component (typically a quartz crystal).

A given percentage of time base inaccuracy results in the same percentage inaccuracy in frequency reading. Equation 30, which was developed above to evaluate the effect of a one-percent inaccuracy in reference voltage for a voltage-based measurement system, can also be used to evaluate the effect of a one-percent inaccuracy in the time base of a frequency-based measurement system. The values in Table 10 are based on the air meter characteristic curve described by Equation 2, with one-percent tolerance on the time base. If the expected tolerance on the time base in the system is other than 1%, the values in Table 10 can be scaled accordingly.

Table 10. Effect of time base tolerance

Percentage change in indicated flow due to 1% time base change			
Flow (g/s)	**Nominal output (Hz)**	**Δoutput (Hz)**	**%flow change**
3.5	2030.111	20.30	2.15
10	3192.544	31.93	2.48
25	4549.817	45.50	2.69
50	5852.036	58.52	2.82
100	7451.924	74.52	2.92
200	9417.526	94.18	3.00
340	11220.83	112.21	3.05

The results shown in Table 10 show that, for a typical air meter characteristic, the effect of time base accuracy on a frequency-based system is slightly more significant at high flow than at low flow.

It should be noted that, for convenience, the results in Table 10 are presented for a 1% time base error. In actual practice, quartz crystal accuracy is much better than this (a 1% error in a wristwatch crystal would result in a timekeeping error of over 14 minutes per day!), so errors in a real system will be greatly reduced compared to those presented here.

INDUCED ELECTRICAL NOISE – The underhood environment in an automobile contains many potential sources of electrical transients. Motors, clutches, solenoids, and the spark ignition system can all produce electromagnetic interference that can be coupled into other systems. If such noise is coupled onto the signal line of a voltage-based air meter system, the resultant signal-plus-noise voltage will misrepresent the flow. Equation 15 can be used to evaluate the flow error corresponding to a level of noise voltage. If the noise is random, filtering can be done either in hardware or in software to reduce the error. Care must be taken that the filtering does not impair system transient response.

Special care must be taken if the voltage readings are taken synchronously with engine events. For example, if readings are taken once per cylinder event, and if spark plug noise is coupled into the voltage signal, the induced noise can no longer be considered random. Voltage sampling at a fixed phase angle of the noise signal can produce a consistent offset reading relative to the true flow due to aliasing. The offset may change as engine speed and load change. A thorough analysis of this effect is beyond the scope of this paper, but this cannot be ignored in system implementation.

A frequency-based system is not as susceptible to these noise sources for the same reason FM radio is not bothered by lightning to the extent AM radio is. Interface circuitry in the engine controller can be designed with appropriate filtering and hysteresis to effectively reject electrical noise without losing the information in the signal. In addition, the voltage-to-frequency conversion process internal to the air meter constantly integrates the internal signal voltage, so that the high and low extremes of the noise signal are inherently cancelled. This integration results in the frequency signal containing information about the complete time history of the flow since the last frequency output transition. Aliasing concerns discussed in the previous paragraph are not an issue with a frequency-out air meter.

FLOW NOISE – The flow through an air meter may not be perfectly steady, even under steady-state engine operation. Localized turbulence may be present, due to protuberances in the inlet ducting upstream of the air meter. In a voltage-based system, the presence of the noise can dither the output voltage through several A/D converter counts. If the noise is truly random, averaging this noisy signal can effectively add bits of resolution to the capability of the A/D converter. Filtering this noisy signal must be done in such a way that the transient response of the air measurement system is not degraded. The system must still be able to respond properly to flow changes due to rapid throttle movement.

For a frequency-based measurement system, the flow-induced noise is present on a voltage internal to the air meter circuitry. The voltage-to-frequency conversion process in the air meter integrates this voltage, so the noise on the output signal, present as a modulation in the output frequency, will be reduced.

CONCLUSIONS

Many factors influence the effective accuracy of an air meter signal. Voltage-based and frequency-based systems have different sets of conditions which must be considered. One factor that can enter into the selection process is simply the availability of an appropriate input, either an available A/D channel or an available timer input. The capabilities of engine controllers, in terms of A/D converter resolution, voltage reference accuracy, time base accuracy, processor capability, etc., are also factors to consider. Either a voltage-based or a frequency-based system can be implemented well or implemented poorly. The analysis approach presented above can be used to compare implementations for specific system constraints.

While specific conclusions are dependent on individual system capabilities which must be evaluated on a case-by-case basis, it is possible to summarize some general conclusions, as follows:

1. Measurement resolution of a voltage-out air meter based system improves as the number of bits of A/D converter resolution increases.
2. Measurement resolution of a frequency-out air meter based system improves as the timer resolution increases.
3. For a typical hot-wire air meter curve shape, measurement resolution of a voltage-based air meter system is worst at the lowest flow and best at the highest flow.
4. For a typical hot-wire air meter curve shape, measurement resolution of a frequency-based air meter system is best at the lowest flow and worst at the highest flow.
5. For a frequency-based air meter system, an algorithm that accumulates a number of air meter signal periods before doing a calculation can improve effective flow resolution.
6. To achieve the best possible resolution at any flow, the air meter output should be scaled to use the entire available voltage range over the flow range expected for the application.
7. An air meter with a straight-line output-vs.-flow characteristic results in very coarse resolution at low flow, for both voltage-based and frequency-based systems.
8. Both voltage-based and frequency-based systems can have inaccuracies associated with tolerance on the voltage reference or time base reference, respectively. Comparing voltage-based to frequency-based systems, typical voltage reference accuracy results in a higher flow error than typical time base accuracy. Error associated with voltage reference tolerance can be eliminated by using a ratiometric interface, but this results in significant additional complexity and cost, both at the component and the system level.
9. Voltage-based air meter systems are more susceptible to be influenced by both flow noise and electrical noise than frequency-based air meter systems. Special care must be taken if the source of the noise is synchronous with the voltage measurement interval.