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Effects of Differential Pressure Sensor Gauge-Lines and Measurement Accuracy on Low Pressure EGR Estimation Error in SI Engines

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Rani Kiwan, Anna Stefanopoulou, and Jason Martz
University of Michigan

Gopichandra Surnilla, Imtiaz Ali, and Daniel Styles
Ford Motor Company

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Abstract

Low Pressure (LP) Exhaust Gas Recirculation (EGR) promises fuel economy benefits at high loads in turbocharged SI engines as it allows better combustion phasing and reduces the need for fuel enrichment. Precise estimation and control of in-cylinder EGR concentration is crucial to avoiding misfire. Unfortunately, EGR flow rate estimation using an orifice model based on the EGR valve ΔP measurement can be challenging given pressure pulsations, flow reversal and the inherently low pressure differentials across the EGR valve. Using a GT-Power model of a 1.6 L GDI turbocharged engine with LP-EGR, this study investigates the effects of the ΔP sensor gauge-line lengths and measurement noise on LP-EGR estimation accuracy. Gauge-lines can be necessary to protect the ΔP sensor from high exhaust temperatures, but unfortunately can produce acoustic resonance and distort the ΔP signal measured by the sensor. With 30 cm gauge-lines, the lower bound on EGR valve ΔP required to maintain the EGR estimation error within ±1% increases from 4 to 10 kPa which is detrimental to engine efficiency. This paper proposes an extension of a lumped parameter model to correct for the gauge-line distortion of the ΔP signal. This correction lowers the ΔP bound back to 4 kPa. Low pass filtering is required before the differentiation of the noisy ΔP signal within the lumped parameter modeling. Filtering with the appropriate cut-off frequency maintains the ΔP lower bound despite the gauge-lines. Furthermore, a ΔP sensor with the appropriate response mimics the flow inertial lag, and further reduces the ΔP bound to 1, 1.7 and 3 kPa for ΔP sensor accuracies of ±0.1, ±0.25 and ±0.5 kPa respectively.

Introduction

Future spark ignited (SI) engines are expected to incorporate more aggressive downsizing to reduce pumping and relative frictional losses to meet increasingly stringent fuel economy regulations. The resulting drop in performance with reduced engine displacement is compensated for by turbocharging. Unfortunately, the efficiency benefits from further downsizing and boosting are restricted in part due to the high load spark retard and fuel enrichment required to respectively mitigate knock and excessive exhaust temperatures [1, 2, 3].

Cooled external exhaust gas recirculation (EGR) is of interest given its potential to reduce both knocking tendency and exhaust gas temperatures [1, 2, 3, 4]. Compared with high pressure (HP) loop implementations, the low pressure (LP) EGR configuration is a better alternative at the low engine speeds prevalent under normal driving conditions [5]. In either case, miscalculation of EGR fraction can be detrimental. Excessive EGR fractions can result in misfire and partial burning [6], and insufficient EGR can cause knock. Therefore, EGR flow must be accurately estimated and controlled.

The EGR estimation problem has been a topic of interest in the scientific community for some time. In 1997, Azzoni et al. proposed a model for estimating EGR flow rate based on sensors available at the time [7], and this topic continues to be addressed [8, 9, 10, 11]. According to [8, 9], the accuracy of EGR mass flow rate estimations made with the steady orifice equation suffers from the unsteady pulsating nature of the LP-EGR flow along with the typically small pressure differentials (ΔP) across the EGR valve. While an increased pressure drop across the EGR valve as shown in Figure 1 – introduced by throttling the air intake system (AIS) throttle – improves the EGR estimation [8, 9], it decreases engine efficiency[1]. Hence, it is of interest to achieve satisfactory EGR estimation accuracy with minimal average pressure differential ($\overline{\Delta P}$) across the EGR valve in order to maximize the pumping benefit of LP-EGR.

[1] Due to the inherently small pressure differentials in LP-EGR systems present to drive the EGR flow, the desired EGR flow rate cannot be achieved in some cases even with a wide open EGR valve. Those systems can be equipped with an AIS throttle to provide a sufficient ΔP when needed to attain the desired EGR flow. Nevertheless, AIS throttling can be necessary even when the required EGR flow can be achieved with a wide open AIS throttle due to the poor EGR estimation accuracy at small ΔP's. It is of interest to minimize or eliminate the AIS throttling in those particular cases.

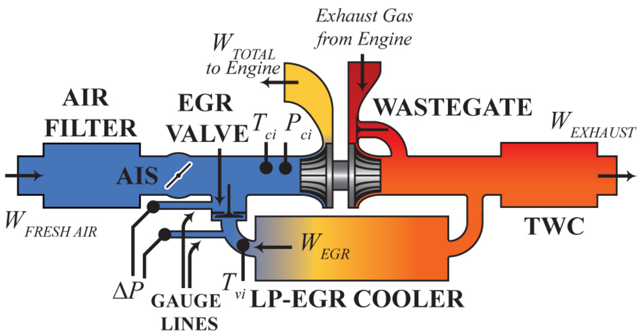

Figure 1. LP-EGR configuration showing the flow rates and sensor measurements of interest.

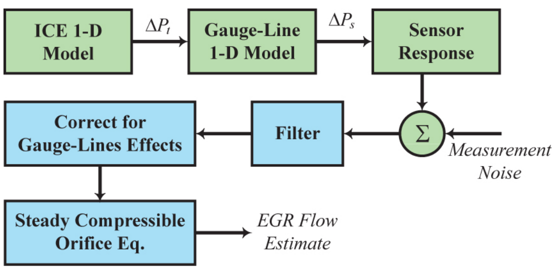

Figure 2. Block diagram summarizing the model of the hardware *(green)* and EGR flow estimation algorithm *(blue)*. The distorted ΔP signal due to gauge-line amplification and attenuation, sensor lag, and measurement noise is low-pass filtered, corrected for gauge-line effects using the extended lumped parameter model, and then used in the steady compressible orifice equation.

This paper builds upon our previous work [12] on determining the optimal ΔP sensor bandwidth and sampling rate that minimize the $\overline{\Delta P}$ required to maintain the LP-EGR estimation error within ± 1%. Having this analysis in place, this paper further investigates the effects of ΔP sensor gauge-line length and measurement error on EGR estimation accuracy. The results of our previous work are first summarized, then the effect of gauge-lines on the EGR estimation error is investigated using a 1-D GT-Power model of a 1.6 L GDI turbocharged engine with LP-EGR. The lumped parameter model developed by by Nagao and Ikegami [13] to approximate (absolute) pressure distortions in the gauge-lines is extended to correct for gauge-line related distortions of a differential pressure measurement. Its effectiveness is then assessed both in the absence and presence of ΔP measurement errors. Finally, the effects of ΔP sensor response are accounted for along with gauge-line and measurement errors. A summary of the models of the hardware and the EGR estimation algorithm is depicted in Figure 2 where the effects of the intermediate blocks between the engine 1-D model and the steady compressible orifice equation are considered and analyzed one at a time.

Sensor Response & Sampling Rate Effects on EGR Estimation Errors

In previous work [12], we investigated the effects of EGR valve ΔP sensor response and sampling frequency f_S on LP-EGR mass flow rate estimation accuracy without accounting for the effects of ΔP sensor measurement error and gauge-line length effects. A fast running 1-D GT-Power model of the Ford 1.6 L EcoBoost with an added LP-EGR loop and AIS throttle was developed to simulate LP-EGR flow at engine loads of 2, 5, 10, 15 and 20 bar brake mean effective pressure (BMEP) and engine speeds of 1000, 1500, 2000 and 3000 RPM. For each case, the EGR valve lift and AIS throttle angle were swept over their domain of operation at a constant load. The resulting LP-EGR flow rates for various EGR valve openings are shown in Fig. 3. Along with the ΔP sensor measurement, cycle averaged measurements of the EGR valve inlet temperature T_{vi}, and the pressure and temperature upstream of the compressor (p_{ci} and T_{ci} respectively) were assumed to be available (Fig. 1). The estimated EGR mass flow rate $\widehat{W}_{EGR}$ was computed using the steady compressible orifice equation:

$$\widehat{W}_{EGR}\left(\Delta P, p_{ci}, T_{vi}, T_{ci}\right) = \begin{cases} \Psi\left(P_r, p_{ci}+\Delta P, T_{vi}\right) & \text{if } \Delta P \geq 0 \\ -\Psi\left(P_r, p_{ci}, T_{ci}\right) & \text{if } \Delta P < 0 \end{cases} \tag{1}$$

where:

$$\Psi\left(P_r, p_0, T_0\right) = C_D A_T \frac{p_0}{\sqrt{RT_0}} P_r^{\frac{1}{\gamma}} \sqrt{\frac{2\gamma}{\gamma-1}\left(1-P_r^{\frac{\gamma-1}{\gamma}}\right)}, \tag{2}$$

and

$$P_r = \begin{cases} \max\left(p_{ci}/\left(p_{ci}+\Delta P\right), P_{r,CR}\right) & \text{if } \Delta P \geq 0 \\ \max\left(1+\Delta P/p_{ci}, P_{r,CR}\right) & \text{if } \Delta P < 0 \end{cases} \tag{3}$$

where γ, C_D, A_T, and $P_{r,CR}$ are the ratio of specific heats, the EGR valve discharge coefficient, the cross-sectional area at the valve throat, and the critical pressure ratio (below which choked flow is obtained) respectively. The error in the estimated LP-EGR percentage is defined as:

$$\epsilon = 100\frac{\widehat{W}_{EGR} - W_{EGR}}{W_{TOTAL}} \tag{4}$$

where W_{EGR} and W_{TOTAL} are the cycle-averaged EGR and total (EGR plus air) engine mass flow rates from 1-D model respectively. The GT-Power simulation results and orifice equation model errors were obtained by sweeping the EGR valve and the AIS throttle at various speeds and loads exercising also the throttle and waste-gate as described in [12].

First the LP-EGR estimation error ϵ was obtained using the cycle averaged ΔP across the EGR valve ($\overline{\Delta P}$) in the steady orifice equation (Eq. 1). This value is representative of the measurement from a ΔP sensor with very low bandwidth and requires a lower ΔP bound of 10 kPa to keep ϵ within ±1% (Fig. 4, black asterisks). If instead, the crank-angle (CA) resolved ΔP was used in the steady orifice equation (quasi-steady formulation), the lower bound on $\overline{\Delta P}$ can be reduced to 4 kPa while maintaining EGR estimation error ϵ within ±1% (Fig. 4, blue asterisks). This case represents a measurement from a ΔP sensor with negligible lag (~ infinite bandwidth $f_C = \infty$) sampled at every crank-angle. Between these extremes, an optimal lower bound on $\overline{\Delta P}$ of 1 kPa (required for $|\epsilon| \leq$ 1%) can be achieved using a ΔP sensor with a bandwidth (f_C) of ~240 Hz (Fig. 4, green asterisks). The ΔP sensor lag mimics the flow lag due to inertial effects that are not captured within the steady compressible orifice equation (Eq. 1), and therefore improves the estimation accuracy of $\widehat{W}_{EGR}$. Finally it should be noted that although sampling at every crank-angle corresponds to a sampling frequency f_S of between 6 and 18 kHz at engine speeds between 1000 and 3000 RPM respectively, our simulations have shown no improvements in the LP-EGR estimation accuracy when f_S is increased beyond 1 kHz [12].

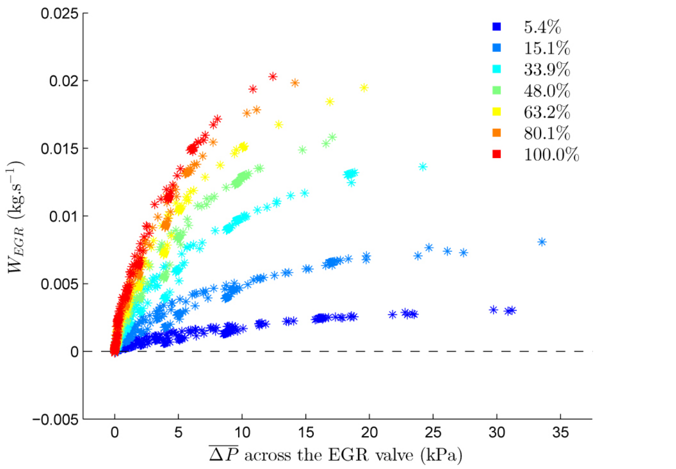

Figure 3. LP-EGR flow versus $\overline{\Delta P}$ for a selection of the simulated EGR valve openings.

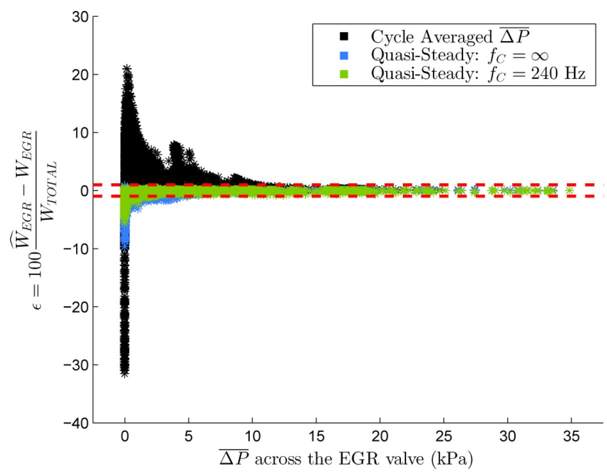

Figure 4. Error in the estimated EGR percentage versus $\overline{\Delta P}$ using the steady compressible orifice equation using cycle-averaged ΔP *(black)*, CA resolved ΔP and negligible sensor lag *(blue, $f_C = \infty$)*, and CA resolved ΔP and sensor bandwidth of 240 Hz *(green, $f_C = 240$ Hz)*. The ±1% error bounds are shown with dashed red lines.

The results depicted in Fig. 4 did not account for the effects of ΔP sensor gauge-line lengths and measurement errors on the LP-EGR estimation error which are the topics of this paper. The ΔP sensor lag is initially assumed to be negligible when evaluating gauge-line length effects and measurement noise error effects. Finally the paper concludes with a complete picture summing up all of the effects, including the ΔP sensor response.

Gauge-Line Length Effects on EGR Estimation Errors

Pressure sensing lead lines, or gauge-lines, are part of the ΔP measurement systems. These gauge-lines are necessary to protect the ΔP sensor from excessive temperatures, or due to space constraints and packaging restrictions. Unfortunately, acoustic resonance is excited within the lines under pulsating conditions which depending on pulsation frequency and gauge-line length result in the amplification or attenuation of the pulsations. The pressure differential at the ΔP sensor is therefore distorted and different from the actual pressure differential at the valve taps, which can in some cases lead to significant EGR mass flow rate calculation errors, also known as gauge-line errors [14].

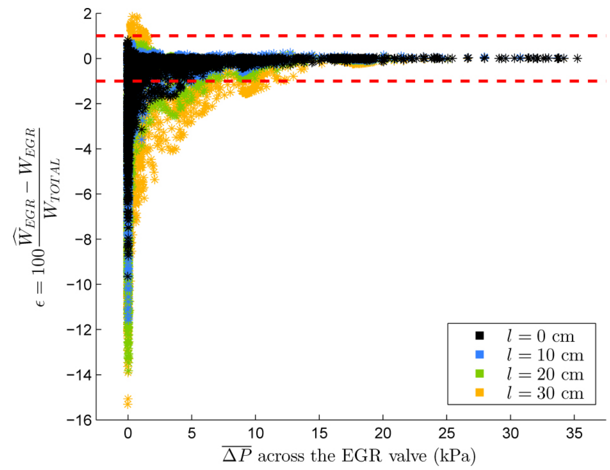

Figure 5. Error (mostly underestimation) in the estimated EGR percentage versus $\overline{\Delta P}$ using the steady compressible orifice equation and CA resolved ΔP (with negligible sensor lag) for different gauge-line lengths. The results show that a minimum average ΔP of 10 kPa is needed to maintain EGR estimation error within ±1% for 30 cm gauge-line lengths.

In order to quantify the effects of the ΔP sensor gauge-line lengths on LP-EGR estimation error, a second GT-Power model is used where the gauge-lines are modeled as straight round tubes with lengths varying from L = 10 to 30 cm. The pressure amplification and attenuation in the gauge-lines are simulated in-isolation from the engine fast running 1-D model since the small discretization lengths used for gauge-line tubes require a small simulation time step that makes the combined engine and gauge-lines system simulations computationally expensive. The pressures and temperatures upstream of the EGR valve at the gauge line tap, obtained from the previous engine simulations, are imposed as time-varying boundary conditions at one end of the tube upstream of the EGR valve. A similar step is performed for the open end of the tube downstream of the EGR valve using the pressure and temperature downstream of the valve. The other end of the upstream and downstream tubes is treated as closed to model the gauge-line termination at the ΔP sensor ports. Grid sensitivity analysis on the gauge-lines 1-D model was performed to ensure that the pressures at the both sensor ports were insensitive to spacial discretization. Starting with discretization length of 25 mm, several iterations are performed where the discretization length of the round tubes is halved following each iteration until the estimated pressure traces converge. The estimates of the pressure traces at the end caps (sensor ports) were considered to converge when the root-mean-square (RMS) of the difference between the traces from consecutive iterations was less than 0.05 kPa. A final discretization length of around 3 mm was used to ensure grid independence.

The simulated pressure traces at the sensor ports for gauge-line lengths of 10, 20 and 30 cm are then used in the steady orifice equation (Eq. 1), and the corresponding errors in the estimated LP-EGR percentage ϵ are computed and compared to the error obtained for the baseline case with no gauge-lines (L = 0 cm). Figure 5 shows this error versus $\overline{\Delta P}$ for different gauge-line lengths. The lower bound of 4 kPa on $\overline{\Delta P}$, required to keep ϵ within ±1% when ΔP is read directly at the tap ($L = 0$ cm), remained almost unchanged when 10 cm gauge-lines are introduced upstream and downstream of the EGR valve ($L = 10$ cm). The EGR estimation accuracy deteriorates however as longer gauge-line are used ($L = 20, 30$ cm). Higher lower bounds of 6 and 10 kPa are required to maintain the same EGR estimation accuracy when 20 and 30 cm (respectively) gauge-lines are used. This is undesirable given that the increased $\overline{\Delta P}$ across the EGR valve can be detrimental to the engine's efficiency because of the increased pumping work associated with the higher pressure differentials between the intake and exhaust manifolds. Note also that the error in Fig. 5 is typically negative indicating an underestimated EGR flow which could cause high cyclic variability and even misfires.

Correcting for Gauge-Line Errors

A lumped parameter model was developed by Nagao and Ikegami [13] in order to model the amplification and attenuation of the pressure signal through the gauge-lines. The model relates the pressure at the sensor port p_s to the pressure at the gauge-line tap (p_t) through the 2nd order non-linear differential equation:

$$\alpha \frac{d^2 p_s}{dt^2} + \beta \frac{dp_s}{dt}\left|\frac{dp_s}{dt}\right| + p_s = p_t \tag{5}$$

where α is a function of geometry and speed of sound, and β is a function of geometry, speed of sound, friction and the average pressure at the tap. The non-linear term in Eq. 5, $dp_s/dt|dp_s/dt|$ is representative of non-linear friction losses [13]. Botros et. al investigated the accuracy of this model (Eq. 5), and reported that it can be applied to moderate gauge-line lengths ($\lesssim 1.3$ m) with its accuracy slightly decreasing with increased pulsation frequency and amplitude [15].

With the lumped parameter model (Eq. 5) correctly tuned, and the pressure measurement p_s, the actual pressure signal at the tap p_t can be estimated. But in the case of a ΔP measurement, only the measurement of the difference of the upstream and downstream pressure signals at the sensor ports is available; thus, Eq. 5 does not apply. Given that the pressure pulsations down stream of the EGR valve (pre-compressor) are small compared to those upstream of it (post-turbine), the pressure pulsations downstream of the EGR valve can be neglected. It follows that $dp_s/dt \simeq 0$ and $d^2p_s/dt^2 \simeq 0$ at the downstream side. Hence we can write $p_{s,d} \simeq p_{t,d}$ where $p_{s,d}$ and $p_{t,d}$ are the respective pressures at the sensor and the tap downstream the EGR valve. Expressing Eq. 5 for the pressures at the sensor and the tap upstream the EGR valve, $p_{s,u}$ and $p_{t,u}$, and subtracting $p_{s,d}$ and $p_{t,d}$ from the left hand and right hand sides respectively, we get:

$$\alpha \frac{d^2 \Delta p_s}{dt^2} + \beta \frac{d\Delta p_s}{dt}\left|\frac{d\Delta p_s}{dt}\right| + \Delta p_s = \Delta p_t \tag{6}$$

where $\Delta p_s = p_{s,u} - p_{s,d}$ and $\Delta p_t = p_{t,u} - p_{t,d}$. For each of the simulated cases in the 1-D model, the least sum of square error (LSSE) estimates of α and β were determined where the error was defined as the difference between the right and left hand sides of Eq. 6. The values of α and β for a given gauge-line length L, were then set to the average of their corresponding LSSE estimates obtained from all operating conditions with the same gauge-line length, and Eq. 6 was used to estimate the actual ΔP at the taps from the distorted ΔP signal seen at the sensor ports. The corrected ΔP signals were then used in the steady orifice equation (Eq. 1), and the corresponding error in the estimated EGR percentage ϵ is shown in Fig. 6. The EGR estimation accuracy was improved; the lower bound on $\overline{\Delta P}$ required to keep ϵ within ±1% is reduced to 4 kPa for the cases with 20 and 30 cm gauge-lines and remained at 4 kPa for 0 to 10 cm gauge-lines.

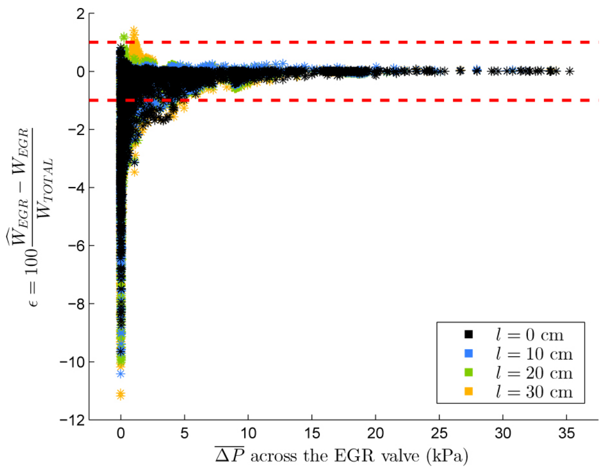

Figure 6. Error in the estimated EGR percentage versus $\overline{\Delta P}$ using the steady compressible orifice equation and CA resolved ΔP (with negligible sensor lag) compensated for the gauge-line effects using the model from Eq. 6. The results show that a minimum average ΔP of 4 kPa is needed to maintain EGR estimation error within ±1% for all simulated gauge-line lengths.

Alternatively, the distortions of the pressure signal due to gauge-line lengths could have been corrected without the need to assume negligible pressure pulsations downstream of the EGR valve if instead a linearized version of Eq. 5 is used. Assuming a lumped parameter model based on a linearized friction model, we get:

$$\alpha \frac{d^2 p_s}{dt^2} + \widetilde{\beta} \frac{dp_s}{dt} + p_s = p_t. \tag{7}$$

Further assuming the same gauge-line lengths upstream and downstream of the valve, and neglecting the difference in the upstream and downstream acoustic velocity resulting from the temperature difference across the valve, it follows that the upstream and downstream α and $\widetilde{\beta}$ are equal, and we can therefore write:

$$\alpha \frac{d^2 \Delta p_s}{dt^2} + \widetilde{\beta} \frac{d\Delta p_s}{dt} + \Delta p_s = \Delta p_t. \tag{8}$$

Using Eq. 8 to correct for the gauge-line effects results in a similar reduction similar to that of Eq. 6 in the lower bound in $\overline{\Delta P}$ required to keep ϵ within ±1% as shown in Fig. 7.

Measurement Noise Effects on EGR Estimation Errors

Although the correction methods for gauge-line length effects proposed in the previous section produce satisfactory results, they both involve the differentiation of the measured ΔP signal. This can be problematic in the presence of high-frequency noise components that are amplified when differentiated. Therefore, in this section, the ΔP sensor measurement noise error is modeled as white noise superimposed onto the sensor ΔP signals to investigate the feasibility of correcting for gauge-line effects under realistic scenarios with measurement noise during the process of estimating EGR mass flow.

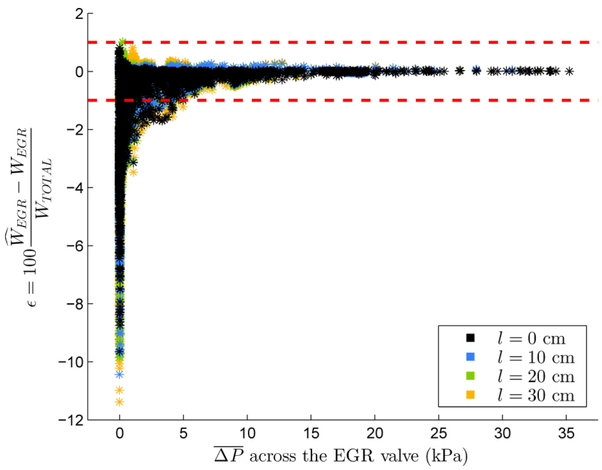

Figure 7. Error in the estimated EGR percentage versus $\overline{\Delta P}$ using the steady compressible orifice equation and CA resolved ΔP (with negligible sensor lag) compensated for the gauge-line effects using the model from Eq. 8. The results show that a minimum average ΔP of 4 kPa is needed to maintain EGR estimation error within ±1% for all simulated gauge-line lengths.

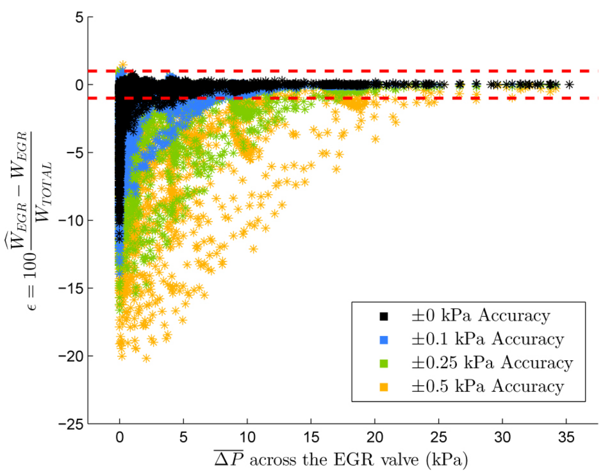

Figure 8. Error in the estimated EGR percentage versus $\overline{\Delta P}$ using the steady compressible orifice equation and CA resolved ΔP (negligible sensor lag) for 30 cm gauge-lines and different ΔP measurement accuracies. Gauge-line distortions in the noisy ΔP signal are corrected for using the model in Eq. 8. The results show that a minimum average ΔP of 22 kPa is needed to maintain EGR estimation error within ±1% for 30 cm gauge-line lengths and ΔP sensor accuracy of ±0.5 kPa.

Fig. 8 depicts the error in the estimated EGR percentage ϵ versus $\overline{\Delta P}$ using the steady compressible orifice equation fed with corrected and noisy ΔP signals with 30 cm gauge-line lengths. As expected, the EGR estimation accuracy is significantly deteriorated. Even a small ΔP measurement error of ±0:1 kPa[2] requires the lower bound on $\overline{\Delta P}$ to be increased from 4 to 7 kPa to keep ϵ within ±1%. Larger measurement errors of ±0:25 and ±0:5 kPa result in further $\overline{\Delta P}$ increases of 15 and 22 kPa respectively.

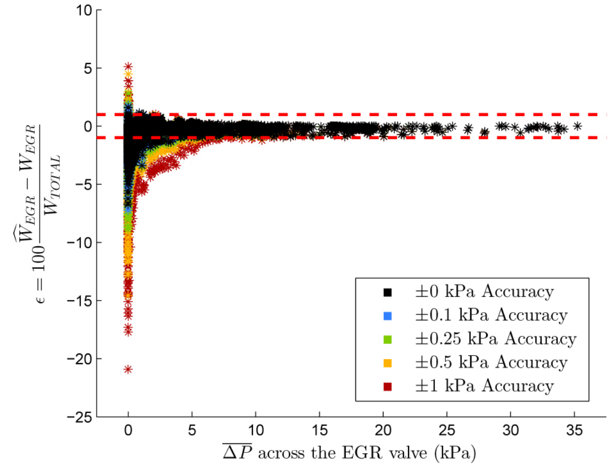

Figure 9. Error in the estimated EGR percentage versus $\overline{\Delta P}$ using the steady compressible orifice equation and CA resolved ΔP (with negligible sensor lag) for 30 cm gauge-lines and different ΔP measurement accuracies. The ΔP signal is low-pass filtered (cut-off frequency f_C = 240 Hz), then gauge-line effects are corrected for using the model in Eq. 8. The results show that the average ΔP can be reduced from 22 kPa to 5 kPa with filtering before correcting for the 30 cm gauge-line distortions given a ΔP sensor accuracy of ±0.5 kPa.

Since the high frequency components of the measurement error are significantly amplified after differentiating the ΔP signal, low-pass filtering of the noisy ΔP signal is considered before using the proposed correction method for the gauge-line effects. Specifically, a 1st order low pass filter with a cut-off frequency f_C of 240 Hz is used. This particular frequency is chosen based on our previous work which showed that the use of this f_C mimics the EGR flow lag due to inertial effects of the studied LP-EGR setup, and therefore, reduces the EGR estimation error ϵ compared to both faster and slower ΔP sensors [12]. Fig. 9 shows the corresponding error in estimated LP-EGR percentage ϵ versus $\overline{\Delta P}$. The lower bound on $\overline{\Delta P}$ required to keep ϵ within ±1% is reduced from 7, 15 and 22 kPa without filtering to 3.5, 3.5 and 5 kPa with filtering for measurement errors of ±0.1, ±0.25 and ±0.5 respectively. The lower bound required for a measurement error of ±1 kPa is 6 kPa (with filtering).

Accounting for Sensor Lag

In our previous work [12], we showed that a ΔP signal measured directly at the tap with a sensor bandwidth of 240 Hz resulted in the optimal EGR estimation accuracy. Given that a ΔP sensor with a bandwidth of 240 Hz is installed with gauge-lines, we are interested in finding an equation similar to Eq. 6 or Eq. 8 that relates the measured lagging sensor output at the end of the gauge-lines $\Delta p_{s,m}$ to the measured lagging output of a sensor directly installed at the taps $\Delta p_{t,m}$, instead of relating their actual lag-free counterparts $\Delta p_{s,a}$ and $\Delta p_{t,a}$. It is convenient to start with the linear Eq. 8, and rewrite it in the Laplace domain:

$$\Delta P_{t,a}(s) = \left(\alpha s^2 + \widetilde{\beta} s + 1\right) \Delta P_{s,a}(s). \tag{9}$$

2. The ±0.1 kPa corresponds to 95% confidence interval; the measurement error is randomly sampled from $\mathcal{N}\left(0, \sigma^2\right)$ where $\sigma = 0.1/2$.

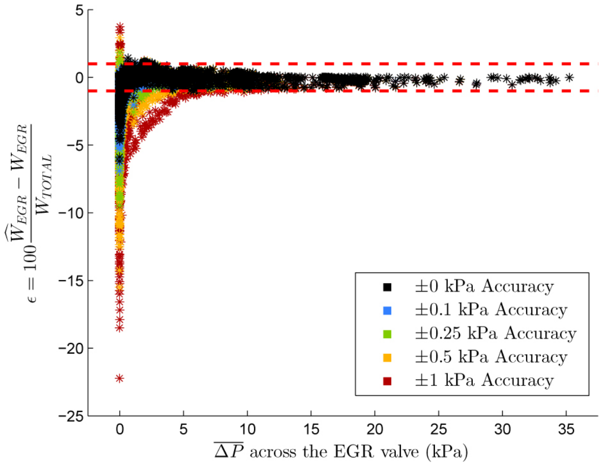

Figure 10. Error in the estimated EGR percentage versus $\overline{\Delta P}$ using the steady compressible orifice equation and CA resolved ΔP (with 240 Hz sensor bandwidth) for 30 cm gauge-lines and different ΔP measurement accuracies. The ΔP signal is low-pass filtered (cut-off frequency f_C = 240 Hz), then gauge-line effects are corrected using Eq. 8. The results show that the average ΔP can be further reduced to 3 kPa with a ΔP sensor accuracy of ±0.5 kPa and bandwidth of 240 Hz.

Modeling the ΔP sensor response as a 1st order low-pass filter with cut-off frequency f_C, we can express the ΔP sensor's measured output in terms of its input as:

$$\Delta P_{s,m}(s) = \left(\frac{2\pi f_C}{s + 2\pi f_C}\right) \Delta P_{s,a}(s). \tag{10}$$

A similar equation can be written for a ΔP sensor installed directly at the taps:

$$\Delta P_{t,m}(s) = \left(\frac{2\pi f_C}{s + 2\pi f_C}\right) \Delta P_{t,a}(s). \tag{11}$$

Combining Eqns. 9 through 11, we get:

$$\Delta P_{t,m}(s) = \left(\alpha s^2 + \widetilde{\beta} s + 1\right) \Delta P_{s,m}(s). \tag{12}$$

Hence, Eq. 9 can be also applied to a measured lagging ΔP signal. The correction for gauge-line effects in this case produces an estimate of the measured signal from a ΔP signal mounted directly at the tap with the same bandwidth as that of the sensor installed at the end of the gauge-lines.

In order to combine the contributions of all the factors discussed in this paper, the ΔP signal distorted due to 30 cm gauge-line lengths is first low-pass filtered to account for the ΔP sensor response, then superimposed with measurement error modeled as white noise, low-pass filtered again to remove high frequency noise, and finally corrected using Eq. 8. The resulting signal is then used in the steady orifice equation (Eq. 1), and corresponding error ϵ is computed. The lower bound on $\overline{\Delta P}$ required for $|\epsilon| \leq 1\%$ is further reduced to 1, 1.7, 3 and 5 kPa for measurement errors of ±0.1, ±0.25, ±0.5 and ±1 kPa respectively (Fig. 10).

Summary and Conclusions

This work builds upon our previous investigation into the effects of ΔP sensor response and sampling frequency on the error in the estimated LP-EGR percentage ϵ. The current work has studied the errors resulting from the ΔP sensor gauge-line lengths and noise related measurement errors, and proposes a method to correct for gauge-line errors in the presence of measurement noise.

Even when the effects of gauge-line lengths and measurement errors were neglected, a lower bound of 4 kPa on $\overline{\Delta P}$ needs to be imposed in order to achieve an EGR estimation error ϵ within ±1% given a ΔP sensor with negligible lag. This is due to the inability of the steady compressible orifice equation to capture the inertial effects that are significant at low values of $\overline{\Delta P}$. Without correction, this lower bound can be maintained at 4 kPa with 10 cm gauge-lines; however, it must be increased to 6 and 10 kPa respectively when 20 and 30 cm gauge-lines are used. These increased pressure differentials will be detrimental to engine pumping work and efficiency.

A lumped parameter model relating the pressures at the both ends of the gauge-lines can be used to correct for the introduced gauge-line distortion of the pressure signal. While this procedure successfully reduces the lower bound on $\overline{\Delta P}$ required for $|\epsilon| \leq 1\%$ back to 4 kPa when measurement errors are neglected, the differentiation of the ΔP signal amplifies the high frequency components of the measurement noise errors and deteriorates the EGR estimation accuracy. In particular, the lower bound on $\overline{\Delta P}$ must be significantly increased to 7, 15 and 22 kPa when 30 cm gauge-lines are used with a ΔP sensor accuracy of ±0.1, ±0.25 and ±0.5 kPa respectively.

Low-pass filtering of the ΔP signal prior to differentiation significantly improves the effectiveness of the lumped parameter model to correct for gauge-line distortion of the ΔP signal. Using a low pass filer with a cut-off frequency (f_C) of 240 Hz results in a required lower bound on $\overline{\Delta P}$ of 3.5, 3.5, 5 and 6 kPa when 30 cm gauge-lines are used along with ΔP sensor accuracies of ±0.1, ±0.25, ±0.5 and ±1 kPa respectively.

Neglecting the effects of gauge-line lengths and measurement errors, using a ΔP sensor with an appropriate bandwidth of 240 Hz reduces the required lower bound on $\overline{\Delta P}$ to 1 kPa; the sensor lag mimics the flow inertia effects and improves the EGR estimate. Using the linearized form of the lumped parameter model, the correction of the gauge-line distortion of the ΔP signal can be applied to the lagging sensor output, reducing the lower bound on $\overline{\Delta P}$ to 1, 1.7, 3 and 5 kPa when 30 cm gauge-lines are used along with a ΔP sensor accuracy of ±0.1, ±0.25, ±0.5 and ±1 kPa respectively, and therefore, reduces potential pumping losses and maximizes the fuel economy benefit of LP-EGR.

References

1. Teodosio, L., De Bellis, V., and Bozza, F., "Fuel Economy Improvement and Knock Tendency Reduction of a Downsized Turbocharged Engine at Full Load Operations through a Low-Pressure EGR System," *SAE Int. J. Engines* 8(4):1508–1519, 2015, doi:10.4271/2015-01-1244.
2. Potteau, S., Lutz, P., Leroux, S., Moroz, S. ., "Cooled EGR for a Turbo SI Engine to Reduce Knocking and Fuel Consumption," SAE Technical Paper 2007-01-3978, 2007, doi:10.4271/2007-01-3978.

3. Alger, T., Chauvet, T., and Dimitrova, Z., "Synergies between High EGR Operation and GDI Systems," *SAE Int. J. Engines* 1(1):101–114, 2009, doi:10.4271/2008-01-0134.
4. Hoepke, B., Jannsen, S., Kasseris, E., and Cheng, W., "EGR Effects on Boosted SI Engine Operation and Knock Integral Correlation," *SAE Int. J. Engines* 5(2):547–559, 2012, doi:10.4271/2012-01-0707.
5. Zhong, L., Musial, M., Reese, R., and Black, G., "EGR Systems Evaluation in Turbocharged Engines," SAE Technical Paper 2013-01-0936, 2013, doi:10.4271/2013-01-0936.
6. Heywood, J. B. Internal combustion engine fundamentals. Mcgraw-Hill New York, 1988.
7. Azzoni, P., Minelli, G., Moro, D., and Serra, G., "A Model for EGR Mass Flow Rate Estimation," SAE Technical Paper 970030, 1997, doi:10.4271/970030.
8. Liu, F. and Pfeiffer, J., "Estimation Algorithms for Low Pressure Cooled EGR in Spark-Ignition Engines," *SAE Int. J. Engines* 8(4):1652–1659, 2015, doi:10.4271/2015-01-1620.
9. Brewbaker, T. “Multivariable diesel low-pressure EGR controller designed by input-output linearization.” In “American Control Conference (ACC), 2015,” pages 31–37. 2015. doi:10.1109/ACC.2015.7170707.
10. Pachner, D. and Beran, J., "Comparison of Sensor Sets for Real-Time EGR Flow Estimation," SAE Technical Paper 2016-01-1064, 2016, doi:10.4271/2016-01-1064.
11. Liu, F., Pfeiffer, J., Caudle, R., Marshall, P. ., "Low Pressure Cooled EGR Transient Estimation and Measurement for an Turbocharged SI Engine," SAE Technical Paper 2016-01-0618, 2016, doi:10.4271/2016-01-0618.
12. Kiwan, R., Stefanopoulou, A. G., Martz, J., Surnilla, G., . “Effects of Differential Pressure Measurement Characteristics on Low Pressure-EGR Estimation Error in SI-Engines.” IFAC-PapersOnLine, 49(11):722–729, 2016.
13. Nagao, F. and Ikegami, M. “Errors of an indicator due to a connecting passage.” Bulletin of JSME, 8(29):98–108, 1965.
14. McKee, R. “Pulsation Effects on Orifice Metering Considering Primary and Secondary Elements.” Proc. of the 22nd Gulf Coast Measurements Short Course, pages 112–118, 1989.
15. Botros, K., Jungowski, W., and Petela, G. “Gauge line effects and DP transmitter response to flow pulsation through orifice plate.” Flow Measurement and Instrumentation, 3(3):130–144, 1992.

Contact Information

Rani Kiwan
University of Michigan
W.E. Lay Autolab
1231 Beal Ave.
Ann Arbor, MI 48109, USA.
rkiwan@umich.edu

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