Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Leakage Detection In a Fuel Evaporative System

Erik Frisk * **and Mattias Krysander** *

* *Department of Electrical Engineering, Linköping University*
SE-581 83 Linköping, Sweden. {frisk,matkr}@isy.liu.se.

Abstract: On-Board Diagnostics (OBD) regulations require that the fuel system in personal vehicles must be supervised for leakages. Legislative requirement on the smallest leakage size that has to be detected is decreasing and at the same time the requirement on number of leakage checks are increasing. A consequence is that detection must be performed under more and more diverse operating conditions. This paper describes a vacuum-decay based approach for evaporative leak detection. The approach requires no additional hardware such as pumps or pressure regulators, it only utilizes the pressure sensor that is mounted in the fuel tank. A detection algorithm is proposed that detects small leakages under different operating conditions. The method is based on a first principles physical model of the pressure in the fuel tank. Careful statistical analysis of the model and measurement data together with statistical maximum-likelihood estimation methods, results in a systematic design procedure that is easily tuned with few and intuitive parameters. The approach has been successfully evaluated on real data measured in a research laboratory.

Keywords: OBD, diagnosis, leakage detection, evaporative fuel system

1. INTRODUCTION AND PROBLEM FORMULATION

Environmentally based legislation, for example the Californian CARB regulations [CAR, 2002], states that the on-board diagnostic system must monitor the fuel system to ensure that vapor does not leak into ambient air. Federal and European regulations have similar requirements. A principle sketch of a common fuel system setup is shown in Figure 1. The system includes a carbon canister which is connected in one end to the fuel tank and the other end is open to the ambient air. The system has a diagnosis valve which is open during normal operation of the engine, and closed when diagnosis is performed. A purge valve connects the canister to the intake manifold of the engine. The canister is regularly purged from hydrocarbons when the purge valve is opened, causing a flow of air through the canister and into the engine and the fuel vapor will be combusted. The fuel tank is equipped with a pressure sensor that measures the difference in pressure between ambient air and the fuel tank pressure.

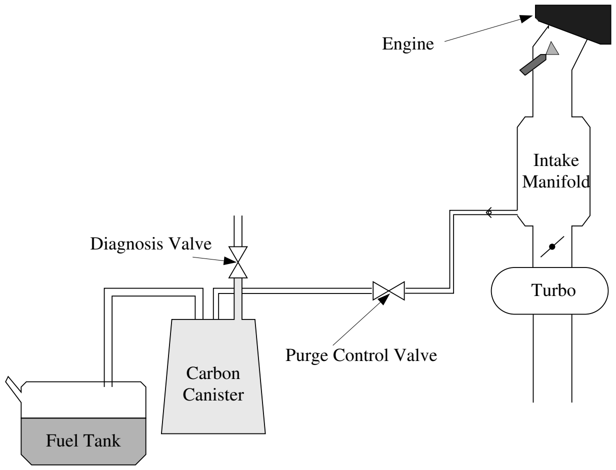

Fig. 1. The evaporative purge system.

The OBD system shall monitor the complete evaporative system for vapor leaks to the atmosphere. Currently the legislative detection requirements move to smaller and smaller leakages. The Californian CARB regulations state that for vehicles with model year 1996 and later, leakage orifices as small as 0.040” (1mm) in diameter must be detected and as of year 2000, the requirement is tightened and detection of leakages as small as 0.02” (0.5mm) is required [CAR, 2002]. In 2005, CARB updated the OBDII regulations such that leak detection checks have to be performed more frequently which also means that detection must be performed under more diverse operating conditions. This will require development of existing methods for leakage supervision [Kobayashi et al., 2004].

Roughly, one can say that there exists two main principles for leakage monitoring: vacuum decay and pressure decay principles. With the vacuum decay principle, an underpressure is created in the fuel tank compared to the ambient pressure and the decay of the pressure difference is monitored and analyzed. The pressure decay principle creates an overpressure in the fuel tank and the pressure difference is monitored and analyzed.

The two principles have their own set of advantages and disadvantages. A disadvantage with pressure decay methods is that, in case of a leak, the overpressure presses fuel vapor out into the atmosphere while in a vacuum decay the air flow is into the fuel tank and thus vacuum decay methods are considered environmentally more safe.

978-1-1234-7890-2/08/$20.00 © 2008 IFAC

10.3182/20080706-5-KR-1001.3491

In addition, pressure decay methods are reported to have a heightened risk of explosion [Remboski et al., 1997]. Also, pressure decay methods require an extra component, a pump to pressurize the fuel tank. The advantage with a pressure decay method is that it has been reported to give higher performance in detecting smaller leakage orifices [Perry and Delaire, 1998].

Typical requirements on a supervision system is low cost and high accuracy. Also, since regulations require that leakage detection checks are performed more frequently [Kobayashi et al., 2004], there is also a need for the detection algorithm to be fast and be able to run in different operating conditions. Based on this discussion, this work presents a new vacuum decay method based on analyzing the differential pressure in the tank. A vacuum decay method is used since it is inexpensive and requires little extra instrumentation, for example no extra pump or an absolute pressure sensor. A key component of the method is a physically based model of the pressure in the fuel tank. Careful use and statistical analysis of the model enables fast and reliable diagnosis under different operating conditions. This work relies on the model developed in [Andersson and Frisk, 2001], where another leakage detection method was proposed. A main difference between [Andersson and Frisk, 2001] and this work is that here a thorough statistical analysis of the problem enables a systematic design procedure. Also, the fact that the air partial pressure in the tank is unknown and non-constant during a leakage is here taken into account.

Section 2 describes the system and its operation to detect leakages. Section 3 describes the physically based model for the tank pressure signal and Section 4 then describes how this model is used in a detection algorithm. The proposed detection algorithm is evaluated in Section 5 and a concluding discussion is given in Section 6.

2. SYSTEM DESCRIPTION AND OPERATION

This section will describe typical operation of the evaporative emissions control system. In normal operation, the diagnosis valve is open and the purge valve is closed. This means that evaporating fuel will be collected in the carbon canister which can be purged by opening the purge valve. To initiate a leakage detection sequence, the diagnosis valve is closed and the purge valve is opened. This results in a pressure drop in the tank which can be seen at $t = 0.5$ and $t = 11$ in Figure 2. After about 2 seconds, the purge valve is closed and the tank system is, in a fault free case, now sealed. The basic idea is now to monitor the pressure signal behavior in the shaded intervals in Figure 2 to detect a possible leakage. In case of a leakage in the tank, the pressure will increase since air will leak into the tank from ambient air. Pressure signal behavior in case of a 1mm leak is shown in Figure 3. A main complication is the effect of evaporating fuel. The effects can be seen by comparing Figures 2 and 3 where it is clear that even though there is no leakage in the tank, the pressure increases similarly to the leakage case. The tank pressure increases until it reaches its saturation pressure and since the saturation pressure is temperature dependent there is a need for the detection algorithm to take this into account to be robust towards different temperatures. An additional complication, which also can be seen in Figure 3 is that the pressure sensor is subjected to a slowly time-varying bias. When the diagnosis valve is open and the purge valve is closed, one can expect that the tank pressure equals ambient pressure, i.e. a sensor reading of 0. However, the pressure reading at $t = 0$ in Figure 3 is distinctly non-zero and this also needs to be considered when designing the detection algorithm.

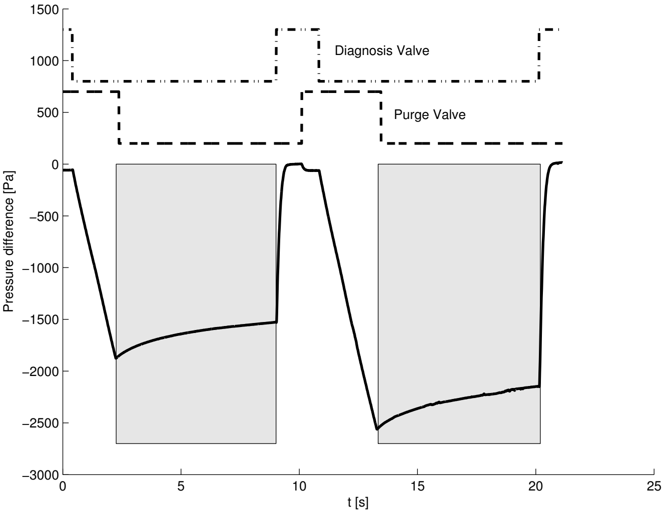

Fig. 2. Typical cycle for leakage detection for the fault free case. Solid line is the pressure measurement and the dashed and dashed-dotted lines indicate the position of the purge and diagnosis valve. The gray areas indicate which data that is used for detecting leaks.

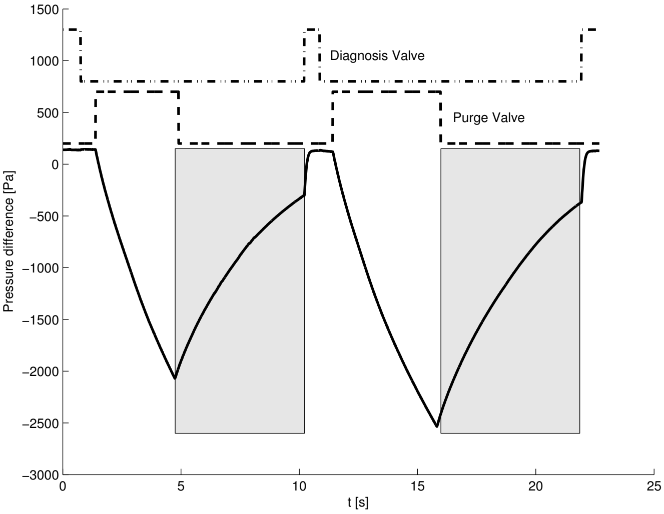

Fig. 3. Cycle for leakage detection for the case with a 1mm leak. Solid line is the pressure measurement and the dashed and dashed-dotted lines indicate the position of the purge and diagnosis valve. The gray areas indicate which data that is used for detecting leaks.

3. MODELING

From the discussion in the previous section, it is clear that leakage detection is performed when an underpressure in the tank has been created and both valves are closed.

During a leak detection test, we assume that the temperature T and volume V in the tank can be considered to be constant. This is reasonable since only about 3kPa is evacuated and the leakage test is performed in less then 10 seconds. In the described situation, the pressure p increases by fuel evaporation and a possible leakage only. To be able to separate pressure traces from cases with small leakages and fuel evaporation from pressure traces with only fuel evaporation, a physical model of the fuel tank pressure valid in the gray shaded intervals in Figure 2 and 3 can be used.

Given a fixed gas volume and temperature in the tank, the ideal gas law implies that the rate of pressure change $\dot{p}$ is proportional to the sum of fuel evaporation mass flow rate W_f and the leakage mass flow W_l directed into the tank, i.e.

$$\dot{p} \sim W_f + W_l \tag{1}$$

The total pressure p in the tank is according to Dalton's law equal to the sum of the partial pressure of air p_a and the partial pressure of fuel vapor p_f, i.e.

$$p = p_a + p_f \tag{2}$$

A simple model for the fuel evaporation mass flow rate W_f is that it is proportional to the difference between the saturated fuel pressure p_f^0 and the fuel vapor partial pressure p_f, i.e.,

$$W_f \sim p_f^0 - p_f \tag{3}$$

The saturation pressure is dependent on temperature and fuel composition.

To get a simple model for the air mass flow W_l into the tank through a leakage area of size A, we assume inviscid and incompressible flow. The air speed v through the hole can under these assumptions be computed with Bernoulli's principle as

$$p_{\text{amb}} = p + \rho v^2/2 \tag{4}$$

where ρ is the density of air and p_{amb} the ambient pressure. By elimination of v using

$$W_l = A\rho v \tag{5}$$

we get the relationship between the air mass flow W_l and the pressure

$$W_l = A\sqrt{2\rho(p_{\text{amb}} - p)} \tag{6}$$

By combining (1), (3), and (6), we get

$$\dot{p} = k_1(p_f^0 - p_f) + k_2\sqrt{p_{\text{amb}} - p} \tag{7}$$

where k_1 and k_2 are temperature and gas volume dependent proportionality constants. Also, the evaporation constant k_1 is dependent on fuel composition, and the leakage constant k_2 on the leakage area A.

As said in previous section, the process is equipped with a sensor measuring the overpressure in the tank. The sensor is assumed to have a slowly varying bias b and the sensor equation can then be written as

$$y = p - p_{\text{amb}} + b \tag{8}$$

Assuming that the bias b and the ambient pressure p_{amb} are constants, i.e. $\dot{b} = 0$ and $\dot{p}_{\text{amb}} = 0$, elimination of p and p_f in the equations (2), (7), and (8) results in the first order model

$$\dot{y} = -k_1 y + k_2\sqrt{b - y} + k_1(p_f^0 + p_a - p_{\text{amb}} + b) \tag{9}$$

During a 10 seconds leakage test, it is assumed that sensor bias b, ambient pressure p_{amb}, temperature, gas volume, fuel composition, and leakage area are constant parameters. This means that b, p_{amb}, k_1, k_2, b, and p_f^0 are constants. However the partial pressure of air p_a is constant only if there is no leakage and this will be considered in the leakage detection method that will be proposed in the next section.

In addition to (9), we will assume that the modeling also includes, given a specific fuel composition, a map of parameter $k_1(V, T)$ relating fuel evaporation rate with the temperature T and gas volume V in the tank. This map can be used to compute fuel evaporation, since the temperature T can be estimated with the ambient temperature which is assumed to be measured. Further, the gas volume V in the tank can be computed using a fuel level sensor. An alternative to use the map $k_1(V, T)$, is to estimate k_1 immediately before we start each leak test by using a vapor generation test as proposed in [Majkowski and Simpson, 2002].

4. LEAKAGE MONITORING METHOD

This section will describe how a leakage detection test can be designed using the model (9) and careful usage of measurement data.

As noted in Section 2, the pressure sensor used suffers from a slowly varying bias. Since it is slowly varying, it can be assumed that the bias is constant during the leakage test period which is about 10 seconds. Now, note that when the diagnosis valve is open and the purge valve is closed, the tank pressure should quickly stabilize around the ambient pressure. This means that the measurement signal y should be 0 if there is no bias. Thus, the current bias can easily be estimated by taking the mean value over data where the diagnosis valve is open and the purge valve is closed. For example, from the first second in Figure 3 it is clear that there exists a bias $\approx$ 150 Pa. The estimated bias can be subtracted from the measurement signal which then can be assumed to be bias free.

The portion of the test cycle that will be used for detection of leakages is, as mentioned in Section 2, the section when air has been evacuated and the purge valve has been closed. The remaining discussion in this section only applies to this portion only unless otherwise stated. The model (9) is a continuous-time description of the pressure signal. Since the collected data is sampled, the detection algorithm need a model in time-discrete form. Here, a simple Euler forward is used with sampling period T_s which results in the equation

$$y_{t+1} = (1 - T_s k_1)y_t + T_s k_2\sqrt{-y_t} + T_s k_1(p_f^0 + p_a - p_{amb}) + \epsilon_t \tag{10}$$

The stochastic noise sequence ϵ_t is introduced to represent model uncertainty and measurement noise. Here, it is assumed that ϵ_t is a white, zero mean Gaussian sequence with unknown variance. This statistical assumption will be validated on measured data in Section 4.2.

4.1 Test quantity design

The basic objective of the detection algorithm is to alarm when the model for fault free operation is inconsistent with the observations. Desirable properties of an algorithm is to be robust against temperature variations, pressure sensor bias, and model uncertainties. The test quantity will be based on a least-squares estimation procedure in a linear regression. As stated in Section 3 a map of parameter $k_1(V,T)$, related to fuel evaporation, is available. Then, define $\alpha = (1 - T_s k_1(V,T))$ and matrices

$$Y = \begin{pmatrix} y_2 - \alpha y_1 \\ \vdots \\ y_N - \alpha y_{N-1} \end{pmatrix},\ E = \begin{pmatrix} \epsilon_1 \\ \vdots \\ \epsilon_{N-1} \end{pmatrix},\ \Phi = \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix}$$

The model (10) can then, for the no leakage case where $k_2 = 0$, be written as

$$Y = \Phi\theta + E \tag{11}$$

where $\theta = T_s k_1(p_f^0 + p_a - p_{amb})$. Note that in a no leakage case the tank is completely sealed and therefore the partial air pressure p_a is constant but unknown. This means that θ in (11) is constant. Important to remember is that this θ is *not* constant in case of a leakage since then p_a increases when air flows into the tank.

A residual can then be computed by a maximum-likelihood estimation of the parameter θ, under a no leakage assumption, and computing a residual

$$\hat{\theta} = \arg\min_{\theta} \|Y - \Phi\theta\|_2 = (\Phi^T\Phi)^{-1}\Phi^T Y \tag{12a}$$

$$R = Y - \Phi\hat{\theta} = (I - \Phi(\Phi^T\Phi)^{-1}\Phi^T)Y \tag{12b}$$

A test quantity can then be computed as

$$T = \frac{1}{\sigma^2} R^T R = \sum_{t=2}^{N} \frac{1}{\sigma^2} r_t^2 \tag{13}$$

where σ is the variance of the residual. A suitable threshold for the test quantity T can then be determined given a false-alarm probability and a $\chi^2(N-1)$ statistical table. Let F_{χ^2} be the cumulative χ^2 distribution and P_{fa} the false alarm probability, then the threshold is computed as

$$J = F_{\chi^2}^{-1}(1 - P_{fa}) \tag{14}$$

To compute T according to (13) we have to determine σ which is unknown. One way to estimate σ is to use the covariance of the residual. Residual (12) could be used to estimate the residual covariance in case there is no leakage. When there is a leakage, model (11) is not valid. The resulting variance estimate then typically becomes significantly too high which would make probability of detection of a leakage unnecessary low. A more suitable way is to use the entire model (10) that is valid also for the leakage case, to estimate σ. The model (10) can then be put on the linear regression form

$$Y_2 = \begin{pmatrix} y_2 \\ \vdots \\ y_N \end{pmatrix},\ \Phi_2 = \begin{pmatrix} y_1 & \sqrt{-y_1} & 1 \\ \vdots & \vdots & \vdots \\ y_{N-1} & \sqrt{-y_{N-1}} & 1 \end{pmatrix}$$

with

$$\theta = \begin{pmatrix} (1 - T_s k_1) \\ T_s k_2 \\ T_s k_1(p_f^0 + p_a - p_{amb}) \end{pmatrix} \tag{15}$$

Maximum-likelihood estimation of θ according to (12) gives a residual

$$r_t = y_t - \begin{pmatrix} y_{t-1} & \sqrt{-y_{t-1}} & 1 \end{pmatrix} \hat{\theta} \tag{16}$$

and the estimate of σ can be obtained from the covariance estimation of the sequence r_t. Note that θ in (15) is *not* constant when there is a leakage since p_a then increases. However, the main objective is to get an accurate variance estimate for the no leakage case and to not get a too high estimate of the variance in case of a leakage. This to ensure that the detectability is not lost in (13) due to a too high σ estimate.

4.2 Validation of statistical assumptions

The test quantity T in (13) is χ^2 distributed under the statistical assumption that the residual (12) is a white Gaussian sequence when there is no leakage in the system. To verify this assumption, fault free data is collected from the real system and a normality plot and a covariance function estimate is computed. Figure 4 shows that the Gaussian assumption for the residual seems reasonable, at least up to 1 standard deviation. Figure 5 shows a covariance function estimate for the residual where also the whiteness property is corroborated.

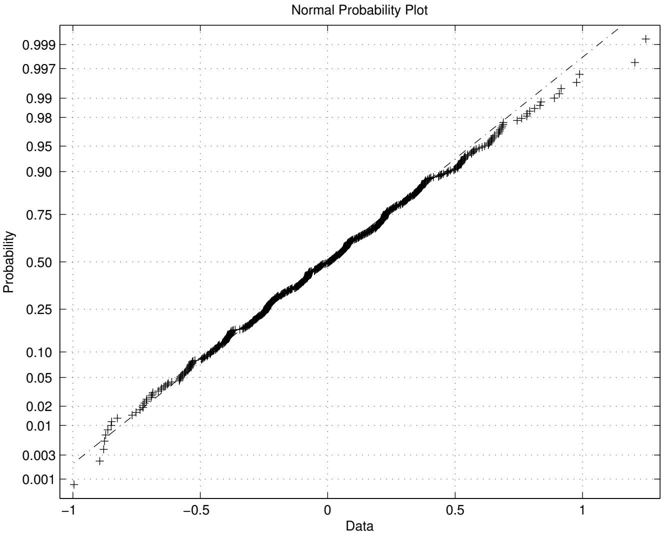

Fig. 4. Normality plot. If data is perfectly Gaussian, the plot will be linear.

4.3 Method summary and discussion

The leakage detection algorithm described in this section is designed to have few tunable parameters for easy design and at the same time being robust enough to work satisfactory in different operating conditions. The algorithm is first summarized and then properties of the algorithm are discussed.

1. Obtain a bias estimation for data where the diagnosis valve is open and the purge valve is closed and compensate measured data accordingly.
2. Take a set of data where the diagnosis valve is closed, air has been evacuated from the tank, and the purge valve is closed.
3. Estimate the noise variance σ using (16).
4. Compute a test quantity T according to (13).
5. Determine a threshold using a predefined false alarm rate and a $\chi^2(N-1)$ distribution table as in (14).

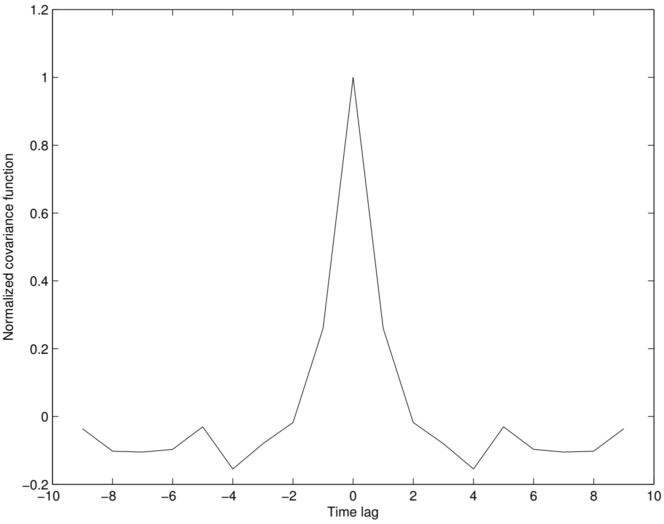

Fig. 5. Estimated covariance function. For a perfect white sequence, the covariance function is a dirac function.

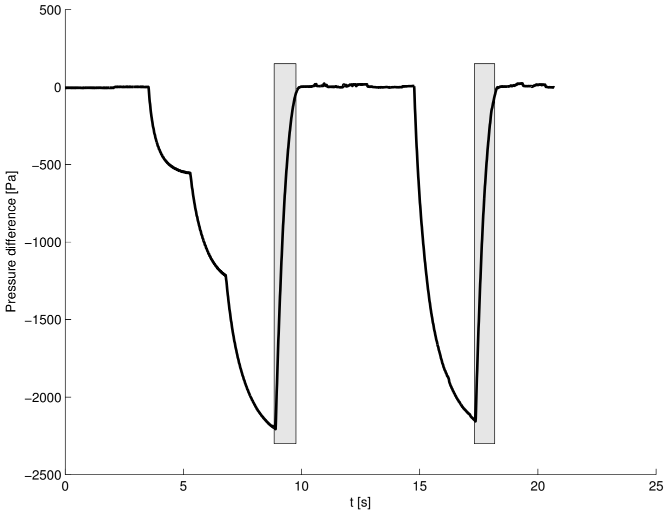

Fig. 6. Cycle for leakage detection for the case with a 3.5mm leak. The gray areas indicate which data that is used for detecting leaks.

A brief discussion now follows on three robustness properties of the algorithm: robustness against disturbances, poor excitation, and data interval selection.

Sudden accelerations of a vehicle cause increased vapor generation in the fuel tank as fuel sloshes in response to the sudden acceleration [Schumacher et al., 1999]. This increase of fuel vaporization might falsely be interpreted as leakage. In [Schumacher et al., 1999] this is avoided by using an algorithm for computing when a test result is valid based on wheel acceleration, fuel tank pressure, and vehicular acceleration during the test. With our method no such algorithm and acceleration measurements are needed, since a sudden increase in the fuel vaporization rate implies a larger noise estimate and thereby a smaller test quantity. Pressure disturbances, caused by for example door closing, are also handled by using the noise variance estimation proposed in (16).

Since the procedure involves a parameter estimation step, excitation is often an issue. Level of excitation, in this problem setting, primarily depends on the level of evacuation. Since the approach does not explicitly use the estimated parameter values, but only the residual, poor excitation will not be a problem and the test quantity will become small even though the estimated parameters are uncertain or even incorrect. The leak detection algorithm thus automatically handles cases with poor excitation.

The number of available data in a selected interval varies with situation, compare for example Figure 2 and Figure 6. It is therefore not possible to use a predefined threshold for all leakage checks and the threshold in step (5) is dependent on the number of samples used in the test.

When comparing the proposed approach to other published vacuum-decay based works it is noteworthy that many works, for example [Majkowski and Simpson, 2002, Perry and Delaire, 1998], propose methods that are based on linear pressure development. Typically, the time needed for the pressure to rise a predefined amount is used to indicate possible presence of a leak. However, when observing measured data, for example in Figure 2, it is clear that the pressure development is far from linear and exhibits evident exponential behavior. Thus, to use such an approach would require careful tuning of data intervals. Possibly, the use of pressure regulators [Perry and Delaire, 1998] can be used to stabilize the pressure in the tank before leakage checks, to increase stability of detection performance and avoid false alarms. Our proposed model based approach is not as sensitive to, for example, data interval selection. This is because the key step is the parameter estimation step which is done based on all data points in the selected interval. Thus, single outliers or small disturbances does not have a major effect on the proposed test quantity.

5. EXPERIMENTAL EVALUATION

This section gives a brief evaluation of the proposed approach on measured data collected from a fuel tank in a laboratory environment. Leakage orifices, ranging from 1mm to 5mm in diameter, have been artificially imposed on the tank system to evaluate detection performance. Due to lack of data it has not been possible to perform a thorough statistical analysis of the performance. Instead, test quantity as a function of leakage size will serve as a performance indicator. The false alarm probability, used in the threshold selection, is set to 1% in this evaluation.

One problem with evaluating the performance is that different test cases have different amounts of data which further means that it is not possible to use the same threshold for all test quantities. Thus, to evaluate the performance we compute a normalized test quantity where T_i in (13) is divided with the corresponding threshold J_i from (14), i.e.

$$T_{i,norm} = \frac{1}{J_i} T_i = \frac{1}{J_i \sigma^2} R_i^T R_i$$

Figure 7 shows the detection performance plotted against leakage diameter. The gray area indicate the region for test quantities based on a number of measured test cycles. Note that the plot is in logarithmic scale which, for example, means that the median value of the test quantity for 1mm leakage is about 3 times the threshold. This performance is

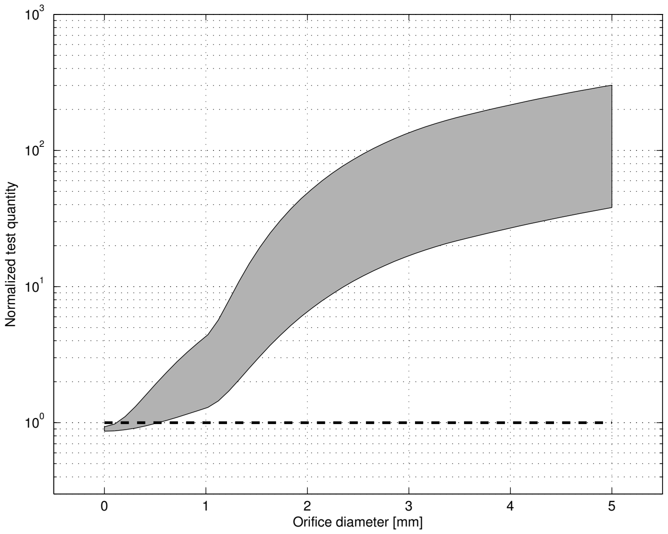

Fig. 7. Detection performance for different leakage sizes. The threshold is the dotted line. Note that the test quantity is plotted in logarithmic scale.

achieved with data lengths ranging from 10 seconds down to 1 second for 5mm leakages.

6. CONCLUSIONS

Leakage detection in a vacuum-decay based fuel evaporative system for automotive vehicles has been considered. The objective has been to develop an easily tuned and systematic detection algorithm that detects small leakages under different operating conditions.

Our proposed solution is based around a first principles physical model of the pressure signal that is supplied by the pressure sensor mounted in the fuel tank. By careful statistical analysis of the model and real data together with statistical maximum-likelihood estimation methods, a leakage detection algorithm is developed. It is worth noting that the model is incomplete in the sense that the dynamics of the partial air pressure in the tank is not described by the model equations. However, careful use of the model still makes it possible to fully utilize the model equations. The tuning of detection thresholds is done by selecting a given false-alarm probability.

Since different levels of excitation, pressure disturbances, and sudden increases of the fuel evaporation rate are automatically handled in the algorithm, it means that no complicated logic is needed to decide if acceptable conditions to run the test are met. This implies that the algorithm has few tuning parameters and a systematic selection of these is possible.

The algorithm successfully detects small leakages using small amounts of data, typically less than 10 seconds but for 0.5mm more data may be needed for reliable detection. For different sizes of leakages, the amount of useful data varies significantly, from about 5 seconds for a 1mm leak to less than a second for a 3.5mm leak. This variation need to be considered in the algorithm, for example when selecting thresholds and this is done automatically in the approach. The approach is fast, requires no expensive additional hardware and has been successfully evaluated on real data measured in a research laboratory.

Acknowledgment

Ingemar Andersson is acknowledged for his expertise in a previous work [Andersson and Frisk, 2001] on leakage detection and for performing all measurements used to evaluate the method proposed in this paper.

REFERENCES

California's OBD-II regulation. *section 1968.2, Title 13, California Code of Regulations*, 2002. `http://www.arb.ca.gov/`.

Ingemar Andersson and Erik Frisk. Diagnosis of evaporative leaks and sensor faults in a vehicle fuel system. IFAC Workshop: Advances in Automotive Control, pages 629–634, Karlsruhe, Germany, 2001.

M. Kobayashi, Y. Yamada, M. Kano, K Nagasaki, H. Miyahara, and N. Amano. Evaporative leak check system by depressurization method. In *General Emissions*, number 2004-01-0143 in SAE Technical paper series SP-1863, SAE World Congress, Detroit, USA, 2004.

S.F. Majkowski and K.M. Simpson. Evaporative emission leak detection method with vapor generation compensation. United States Patent, May 7 2002. Patent Number: US 6,382,017 B1.

P.D. Perry and J.P. Delaire. Development and benchmarking of leak detection methods for automobile evaporation control systems to meet OBDII emission requirements. In *General Emissions*, number 980043 in SAE Technical paper series SP-1335, SAE World Congress, Detroit, USA, 1998.

D.J. Remboski, S.L. Plee, M.B. Woznick, and J.F. Foley. Apparatus and method of detecting a leak in an evaporative emissions system. United States Patent, June 10 1997. Patent Number: 5,637,788.

D. Schumacher, M. Lynch, and D.J. Remboski. Evaporative emission leak detection system and method utilizing on-vehicle dynamic measurements. United States Patent, October 12 1999. Patent Number: US 5,964,812.