A Useful Application of a Simulator for Leak Events in Pipelines

Luis Ángel Alarcón-Ramos
Departamento de Matemáticas Aplicadas y Sistemas
Universidad Autónoma Metropolitana
México, D.F., México
lar@xanum.uam.mx

Pedro Pablo González Pérez
Departamento de Matemáticas Aplicadas y Sistemas
Universidad Autónoma Metropolitana
México, D.F., México
pgonzalez@correo.cua.uam.mc

Abstract*—During the development of an automated system for detecting leaks in pipelines, the test phase with actual and historical leak events is essential to verify the efficiency and effectiveness of detection methods implemented. However, frequently, both direct access to actual leak data and the availability of consistent historical leak data turn out to be extremely complex and difficult activities. In this paper we describe and discuss the performance of a leak event simulator in pipelines. The proposed simulator produces different scenarios with data generated from probability distributions, involving different types of parameters, such as flow, pressure, temperature, noise, vibration and dilation. Events generated by the simulator emulate closely correlated outputs of different components and leak detection sensors, which use methods based on mass balance, acoustics and optics. Simulating a heterogeneous range of events associated with different detection methods not only allows the detection and localization of a leak, but to prevent it before it happens.

***Keywords*—leak detection; leak localization; pipeline; leak event simulator**

I. INTRODUCTION

Pipeline transport is today one of the methods commonly used for the movement of gases, liquids, and suspended solids (fluids) that must be transferred over long distances. Commonly, pipelines are structured and organized as part of large networks of pipelines. Pipeline transport is a fully automated system characterized by low operating costs.

Although pipeline technology is much more efficient and secure than other means of motor transport [1], this does not mean it is risk free. For example, hydrocarbon pipelines are high risk structures if they are not given proper maintenance. This can be preventive or corrective, but both tend to preserve the integrity of the pipelines. The main leaks, spills, illegal connections, vandalism, mechanical impacts, environmental impacts (caused in sea, land and air) of hydrocarbons occur during production, processing or transportation. These events cause serious impacts on biodiversity, so it becomes a priority for governments and companies control and mitigate them [2].

The main causes of pipeline leaks are [3]:

- External interference
- Construction defects
- Repair defects
- Corrosion
- Incorrect operation
- Material failure
- Rupture or leak in joins
- Rupture or leak in seals
- Rupture or leak by prior damage in pipeline
- Ground movements

Much of the proposed automated systems for leak detection described in the last two decades [4, 5, 6, 7, 8, 9, 10] are based on mass balance methods [11, 12, 13]. The mass or volume balance leak detection technique is based on the principle of mass conservation, i.e., the flow entering one end of the duct must be maintained until the other end thereof. Therefore, a leak is identified at the instant when the flow amount is less in the pipeline end. Changes in pressure and flow patterns along the pipeline indicate the presence of a leak [11, 12, 13, 14].

Although mass balance methods are easily installed and have low cost, they are only able to detect and quantify relatively large leaks, not being able to determine in many cases the cause of the leak, the presence of more than one leak or prevent the lake. This problem has given way to the study and development of other leak detection methods based on non-intrusive techniques, such as acoustic methods and optical methods [2], [14]. Thus, we believe that acoustic and optical methods, combined with a mass balance method, would allow not only detecting, locating and quantifying a leak, but also prevent it.

Acoustic signals generated by the presence of leaks in a pipeline play an important role in the detection of leaks in underground pipelines [15, 16]. That is, acoustic signals could be used to determine that a leak or an abnormal event that could lead to a leak has occurred. Acoustic methods are based on the use of sensors installed along the pipeline, which can detect sound waves or disturbances. For example, among other scenarios, a leak generates a noise signal which is detected by the sensors, where the magnitude of the leak can be estimated by the amplitude of the acoustic wave [16]. Unlike other noninvasive methods of leak detection (e.g., ultrasound or Xray) in acoustic methods, the detected energy is released from inside the material being examined; it is also possible to detect dynamic processes associated with structural integrity (crack growth, plastic deformation) [17]. When a pipeline is exposed to a tension force or pressure, the whole structure is affected, so that by placing an acoustic sensor is able to measure those changes. If the pipeline has a deformity, it will also be affected, resulting in a pattern or characteristic background noise. If the deformity increases, the acoustic sensor would be able to measure the increase.

Among the optical methods [14], [18], the method based on optical fiber sensors has been one of the most explored recently. Applying a perturbation to the optical fiber, the light passing through the core is modified, absorbed or dispersed within the fiber, altering the wavelength by either fluorescence or phosphorescence, modifying the polarization, by birefringence and modifying optical phase by changes in the optical path [3]. When the change in one or more of these parameters is detected by the interaction between the optical fiber and the perturbation to be measured, the optical fiber acts as a sensor and can be designed to measure a variety of physical and chemical parameters. Distributed fiber optic sensors are well suited for pipeline monitoring, as has been shown in practice. Leak detection technique based on optical fiber sensors gives a reasonably fast response and is more sensitive than some hardware-based methods [2].

During the development of an collaborative system for detecting leaks in pipelines, the test phase with actual and historical leak events is essential to verify the efficiency and effectiveness of detection methods implemented. In this phase is commonly necessary to adjust the parameters and optimization algorithms. However, frequently, both direct access to actual leak data and the availability of consistent historical leak data turn out to be extremely complex and difficult activities. The degree of complexity and difficulty increases when considering leak events related to different parameters such as flow, noise, vibration, expansion, etc. It is precisely in those cases where the role of a leak simulator is useful.

Taking into account the ideas outlined above, this paper describes and discusses the performance of a leak event simulator in a pipeline. The proposed simulator is able to produce different scenarios with data generated from probability distributions. Events generated by the simulator emulate closely correlated outputs of different components and leak detection sensors, which use methods based on mass balance, acoustics and optics, as already previously entered.

In the next section (section 2), the characteristics of the pipeline and leak events to simulate are described. Section 3 presents the leak event simulator, focusing on the characteristics of the simulated data. A detailed scenario of leak events to simulate is presented in section 4. The results obtained during the interaction between the simulator and a collaborative system for leak detection are presented and discussed in section 5. Finally, section 6 provides some concluding remarks.

II. THE INTRINSIC AND NON-INTRINSIC PARAMETERS OF THE PIPELINE

The main purpose of the leak event simulator is to provide a set of data from various methods for detecting and locating leaks or events on a pipeline. In this sense, an event is defined as that action which could affect the transport of the product through the duct.

At this point, it is important to define the parameters or characteristics of both the pipeline and the product transported, and those parameters that are not part of the pipeline but that depend on the pipeline. Together, both types of parameters will provide the properties to be sensed, which will allow detect and locate events and prevent a leak.

Of course, the most important event is the leak and generally, the literature focuses on the detection and location of leaks, rather than prevention. However, the establishment of a set of detection methods based on a range of different parameters of the pipeline – i.e., mass/volume balance, acoustic, optical - will not only detect and localize a leak, but to prevent it before it happens. Taking into consideration the previous ideas, in this work we refer to the concept of “event” as a circumstance or action that could trigger a leak.

Simulated data of the pipeline parameters will be used to test and tune the performance of a computer system for the diagnosis and prevention of leaks, which is based on the collaborative work of different artificial intelligence techniques. The diagnosis reached by the system will enable the decision making and problem solving for prevent, detect and locate a leak incident.

A useful way of classifying leak detection models is based on the nature of observable parameters. According this taxonomy the leak detection models can be classified into two main groups:

- Models based on equations governing the parameters associated with the normal operation of the pipeline, and here defined as *intrinsic parameters* - e.g., fluid pressure inside the pipeline.
- Models based on parameters that arise as a result of disturbances on the pipeline, and here defined as *non-intrinsic parameters* – e.g., an acoustic wave moving throughout the pipeline as a result of a stroke.

Regarding pipeline parameters previously defined, a set of equations based on conservation of mass and momentum are used in [19, 20], which govern the behavior of the pipeline when there is a leak. This set of equations estimates the variations of some parameters such as speed and fluid pressure. However, it is important to note that although both models are based on the solution of a system of differential equations, they work different. While in [19] the idea is to estimate the behavior of the pressure along the pipeline under the occurrence of a leak, in [20] the system sets the pressure changes caused by leak at the ends of the pipeline, these changes can be seen as a wave traveling through the pipeline. In both cases, the fluid pressure is a key parameter, which is part of what we have named as *intrinsic parameters*. A leak disturbs this parameter, so its analysis allows us to detect and locate a leak.

A leak not only generates pressure changes in product transported, but also generates an acoustic disturbance, due to the friction of the product with the pipeline walls, which will propagate in the pipeline [2], [14], [16]. The impact of objects on the pipeline also generates an acoustic wave traveling through the pipeline [21]. That is, there are at least two acoustic waves produced by different sources and characterized by different features, which when interpreted support the identification and localization of an event. The properties of the last kind of disturbance are part of what we call non *intrinsic parameters*, e.g., when the pipeline is beaten.

Acoustic methods require the use of sensors to detect disturbances or acoustic signals. However, sensed data include not only event or leak signal, but also background signals produced by the normal operation of the pipeline, and signals that disrupt the system, such as the action of the pumps or compressors that move the product through the pipeline [16]. Consequently, one of the main problems in leak detection is to filter or discriminate the signal noise produced by the event, and thus to avoid false alarms [22, 23]. The latter reinforces the hypothesis about the need for other methods of leak detection and location, in order to have a better identification of a possible event.

There are many ways to implement acoustic methods, for example, capturing the acoustic signal by placing a set sensors distributed throughout the pipeline, processing the captured data, and extracting the leak signal [22]. However, the proposed technique, although adequate, its effectiveness depends on the distance between the sensors, proving to be very expensive when the number of sensors increases. Otherwise to reduce the number of sensors is to place the sensors at the ends of the pipeline. The signal detected by the pair of sensors is analyzed for determining its characteristics in both frequency and phase, and thus detect and locate leaks [8], [16], [21]. An important element to consider is how to use the sensors, the sensor can be placed inside the pipeline (invasively), or outside (non-invasive). Of course, the characteristics obtained in the data depend on the type of technique used - that is, invasive or non-invasive.

Acoustic methods represent an appropriate approach to leak detection and location, because they are fast, easy to use and allow localize and estimate a leak [2]. Moreover, acoustic methods allow not only locate a leak, also events that could trigger a leak, such as the sound of a blow or the sound produced by a broken pipeline wall, caused by corrosion. In this sense, acoustic methods may be a good option considering that in addition to detecting the leak can prevent it. However, the leak detection based exclusively on acoustic methods may be characterized by the generation of false alarms, which could be reduced by combining acoustic methods with other detection methods such as mass balance.

Another appropriate approach to leak detection and location is given by optical methods. As acoustic methods, optical methods are fast and allow localize and estimate the leak, however, this technique can be very expensive, but can be very useful in preventing the leak.

Into the optical fibre, the laser light travels from one end to the other through reflection with the walls of this, and when an optical fibre is subjected to small changes in temperature, strain or vibrations, its structure changes (for example, it contracts or expands). A portion of laser light returns to the source from the point where the structure changes, so that it is possible to analyze the characteristics of the returned signal and thereby determine the magnitude of the phenomenon and its location.

The product inside the pipeline is subject to certain pressures, which generally keeps the product at a certain temperature, different from the medium surrounding it. In the case of a leak, the temperature of the product may affect the surroundings of the pipeline, so that an optical fiber placed to the side of the pipeline may detect this change in temperature, and then report the occurrence of that event [18], [24], [25]. Moreover, an optical fiber is capable of detecting, through the acoustic waves, the vibrations in the pipeline, which could be the result of a leak event. The basic principle of this method consists in determining the phase change of the signal traveling in the optical fiber when exposed to vibration, and thus detect and locate a possible event [26, 27].

At this point, it is important to note that the use of optical fiber can also prevent a leak. Also note that the temperature is part of the *intrinsic parameters* of the pipeline, while the vibrations are part of the *non-intrinsic parameters*.

Optical and acoustic methods may, in some cases, to estimate with certainty and relatively quickly the size of the leak [2] without providing a quantification of it. However, optical and acoustic methods may be complemented with other leak detection methods capable of quantifying the size of the leak.

A commonly used approach for estimating the amount of leaked product is through the use of mass balance method, whose principle is based on the conservation of mass. The fundamental idea behind of this method is to determine the difference between the mass/volume of product introduced at one end of the pipeline with the mass/volume of product obtained at the other end [13]. While the method is straightforward to detect a leak, it cannot determine the location of the leak. Therefore, methods as described in [19], [20] are used to determine the location of the leak. There are also other methods to obtain a greater amount of information about the leak event – e.g., using pressure sensors that detect changes in pressure and thus determine the location of the leak.

So far we have discussed three methods for the detection and location of leaks: acoustic, optical and mass balance. Note that the first two permit both leak detection and prevention. Based on these approaches, the simulator proposed in this work contemplates the pipeline parameters shown in Table 1, along with corresponding methods which would be implemented for the detection and interpretation of these parameters.

A simulator based on the above parameters, and simultaneously using detection methods shown in Table 1, could be very useful in the adjustment and testing of systems for detecting and locating leaks. In the next section we discuss how the parameters in Table 1 will be modeled, and how the detection and location methods could deliver its results. Such results could then be sent to a computer system for processing, and eventually produce a result, which would support when taking the actions that correspond to a leak event.

TABLE I. THE LEAK DETECTION METHODS AND THEIR PARAMETERS

Detection and location method	**Parameters**	
	Intrinsic	***Non intrinsic***
Mass balance	Pressure, flow, product speed	-
Acoustic	Changes in acoustic characterizing normal operation of the pipeline, e.g., friction exerted by the product on the walls of the pipeline	Acoustic disturbance produced by an external agent to the duct, e.g., an excavation around the pipeline
Optical	Temperature	Acoustic disturbance, e.g., vibration

III. THE LEAK EVENT SIMULATOR

According to Table 1, three methods of detecting and locating leaks will be considered for the development of the simulator. Each of these methods has certain advantages over the other, but together they complement each other so that it is possible to predict, detect and locate possible events that could cause a leak. Each method will be able to sample and process one or more parameters, producing an output data or result. However, the simulator will not take care of simulating the performance of each method, but the behavior of the output to be produced by each method given the occurrence of an event. Such data will be subsequently processed and interpreted by a leak detection and location system.

A. *Selection of mass balance parameters*

It is hoped that the product transported by the pipeline, once that enters one end and pumped, should come out the other end almost at the same rate with which it comes. However, once a leak has occurred, the amount of product entering the duct is somewhat different from the product leaving the other end of the duct. This is the principle of the models based on mass balance and applies to both liquid and gas products, the latter being more complicated during the implementation of a mass balance method [12].

As already mentioned, mass balance methods require solving simultaneously a set of equations that model the behavior of the product in the pipeline, to determine the location and rate of leak. Mass balance methods rely on the accuracy of the sensors [12] and, unlike optical and acoustic methods, they can determine the magnitude of the leak, once this has occurred. However, the certainty of detection depends on the amount of the leaked product.

From mass balance methods, two main data are considered by the simulator: localization and quantification of the leak. In relation to the leak quantification, it may be developed throughout the simulation, which would mean that in most cases the value will increase, and due to the accuracy of the sensors and the method used to solve model equations, quantification would have some uncertainty, whose behavior is expected to follow a normal distribution. With respect to the location, the simulator will handle a fixed value which, as in the quantization parameter, will have a given uncertainty based on a normal distribution with mean equal to the value of the location.

Another important aspect to consider, when the mass balance method is implemented, is that the leak does not spread immediately, but need to wait a certain time before the leak can be detected. Given this feature, in the simulation unlike acoustic and optical methods, the mass balance method to detect the leak take a while T_{bm} after the leak has occurred.

B. *Selection of acoustic parameters*

As seen in Table 1, there are at least two ways to implement the acoustic method for detecting leaks on a pipeline, where the basic principle is based on interpreting the acoustic waves traveling over the pipeline as a result of an event – e.g., a knock on the pipeline, some excavation near the pipeline, pipeline cracking or a leak. The interpretation of these acoustic waves is not a simple task, due to attenuation that may occur in wave traveling through the pipeline, or simply because the sound wave result of an event has been mixed with the sound waves that are part of the natural operation of the pipeline or the environment (background noise).

For example, in [23], the method of detection and localization is based on the characterization of the acoustic wave by extracting its frequency components using Wavelet Packet Transform, thereby eliminating those signal components that belong to the background noise. As seen in Figure 1, the data are extracted by placing a pair of sensors at the ends of the pipeline, so that the wave generated by the leakage is attenuated by the product traveling in the pipeline, and only those components low frequency can be recovered by applying the transform. Finally, the filtered data are classified by a method of Fuzzy Support Vector Machine, which allows identifying and locating a leak with high accuracy, even more, the method can locate small leaks quickly.

Note that an important aspect of the method proposed in [23] is its ability to detect small leaks, so it would be able to identify the start of a leak and likewise, could prevent their occurrence, interpreting the noise generated for the event as a leak. In this sense, the acoustic method provides for simulating those data based on the detection and localization of an event with some certainty. It is hoped that during the occurrence of a leak event increases certainty – e.g., a certainty of 100% could indicate a leak, instead a certainty of 10% would indicate that something has been detected, not necessarily a leak.

C. *Selection of optical parameters*

Optical fibers allow for a distributed arrangement of sensors throughout the fiber, and also provide a high bandwidth with low signal loss [25]. As the detection method, an optical fiber can detect temperature, pressure, and acoustic vibrations in the pipeline [18].

As a complement to the acoustic method described above, the simulator also consider acoustic signals detected by a detection and localization method based on optical fiber. Thus, the optical method will contribute to the prevention of an event that may result in a leak in the pipeline.

The optical fiber is placed as close as possible to the pipeline, so that it can detect vibrations near the pipeline. When a disturbance occurs, whether on or near the pipeline, the signal travels over optical fiber undergoes a change in the backscatter. This change is detected and interpreted as an acoustic signal, which finally is characterized, allowing determining what type of event emerges from the characteristics of the signal. The optical method is characterized by a high probability of detection with a high sensitivity for the sensing of data [18].

In the optical method, as in the acoustic method, the detection of an event is characterized by a given certainty. Similarly, high certainty could indicate a high probability of leak. Moreover, in the optical method, the location of the leak is very precise, thereby determining the location of the event with a certainty in a very narrow range.

D. A summary of the simulated leak parameters

Table 2 presents simulated data for each leak detection method previously mentioned. Fig. 1 shows a possible configuration scenario involving the operation of these detection and location methods on a particular pipeline. Thus, the simulator will emulate the behavior of the data processed by each detection and location method, which when subsequently analyzed by a computer system, would lead to a more complete result in the detection and prevention of leaks.

TABLE II. SIMULATED DATA FOR EACH LEAK DETECTION METHOD

Leak detection method	*Simulated data*
Mass balance	CEV_{bm} = event certainty. F_{bm} = amount of leaked product. DF_{bm} = uncertainty of amount of leaked product. L_{bm} = event location. DL_{bm} = location uncertainty.
Acoustic	CEV_{ac} = event certainty. L_{ac} = event location. DL_{ac} = location uncertainty.
Optical	CEV_{o} = event certainty. L_{o} = amount of leaked product. DL_{o} = location uncertainty.

It is important to note that the detection of leak events is simulated through the following three levels:

- Prevention level - based on optical and acoustic methods, where the optical method, given the characteristics described above, is the primary method of detection and localization.
- Alarm level - supported mainly by the acoustic method, allowing detecting and locating a leak in its early phase.
- Leak level - based on the mass balance method, together with the other two methods, help to quantify the leak to determine its severity.

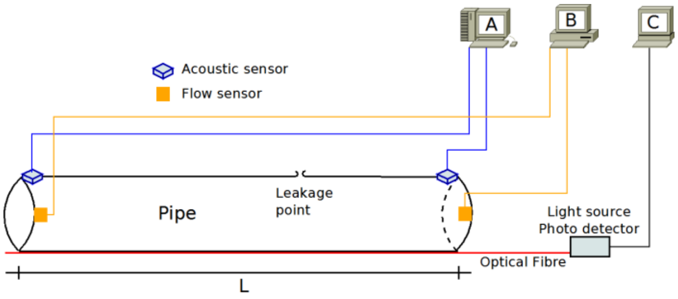

Fig. 1. Configuration scenario: *A*, *B* and *C* represent the methods of mass balance, optical and acoustic respectively, to detect and location leaks.

Other important features of leak events are considered in the simulator: the time at which a certain event was detected, denoted by T_{det}, and the time at which the event begins, denoted by T_{ev}. All detection methods are able to set the detection time, but they cannot set the time at which the event began. In principle, it could be possible estimate the value of T_{ev}, but we propose an initial value for T_{ev} for each method.

Fig. 2 illustrates the workflow of the simulator, showing clearly the stages in which the previously described leak data are generated. For more details on the simulator functionality the interested reader is encouraged to check the available source code, located at http://libio.cua.uam.mx/ls/.

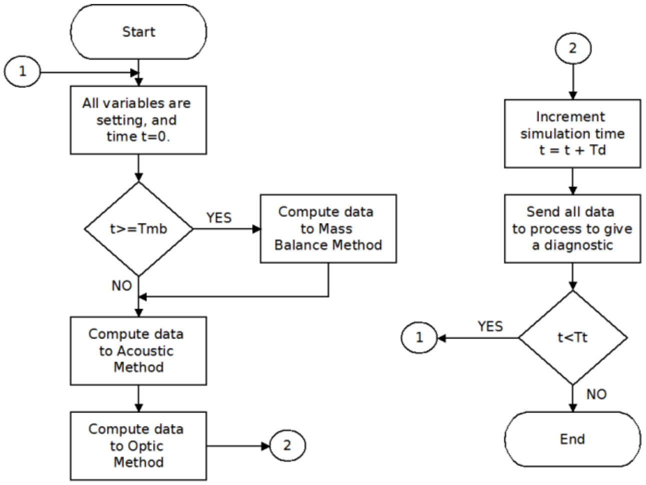

Fig. 2. The workflow of the simulator.

IV. A SIMULATED SCENARIO OF LEAK

The simulated scenario emulates the evolution of a leak, for which we consider that the pipeline is subjected to stress or shock by some external agent, until such intrusion actions cause the leak of product transported by the pipeline. The leak increases in magnitude from a minimum value up to a maximum value.

Consider a pipeline of length L that carries a product – e.g., a liquid or a gas. Consider further that the three detection methods described above - i.e., mass balance, acoustical and optical - are in operation on the pipeline, as shown in Fig. 1. For purposes of the simulator, pipeline characteristics (e.g., diameter and thickness) are not relevant since these are integrated by detection methods on obtaining their results, which are simulated on the basis of the evolution of the leak.

At one point an event is produced on the pipeline, e.g., disturbances caused by shock by very close excavation or deliberate intrusion to the pipeline. The event will evolve to eventually become a leak. Suppose the duration of the simulated scenario is T_t units of time and for practical purposes it begins at time zero. Assume that the leak begins at the instant of time T_{mb}, same instant of time at which the mass balance method may begin with the detection of the leak event.

Given the characteristics of optical and acoustic methods, they will detect the event almost immediately and immediately begin sending data. Table 2 lists the data that both methods offer: certainty of the event ($EVC_o(t)$ and $EVC_{ac}(t)$), location of the event ($L_o(t)$ and $L_{ac}(t)$) and its uncertainty ($DL_o(t)$ and $DL_{ac}(t)$) which, due to the behavior of the scenario, may not necessarily be constant throughout the simulation. It is expected that the detection results produced by the optical method will be better than those produced by the acoustic method, which will be reflected in the value of certainty of the detected event. Typically, the acoustic method provides good results once the leak is generated, so that at the moment the leak event is very near, the acoustic method probably provides certainty values very similar to the optical method. If we consider that the actions associated with the event or disturbance in the pipeline increase your intensity over time, then it is expected that the certainty of acoustic and optical methods also increase. Based on the above, for the given simulation scenario, consider $EVC_o(t)$ and $EVC_{ac}(t)$ increase linearly with time - as shown in Fig. 3 - to a maximum value from which are held constant. The latter happens when the leak occurs at the instant T_{mb} because, once the leak occurred, the data from optical and acoustic methods are very accurate.

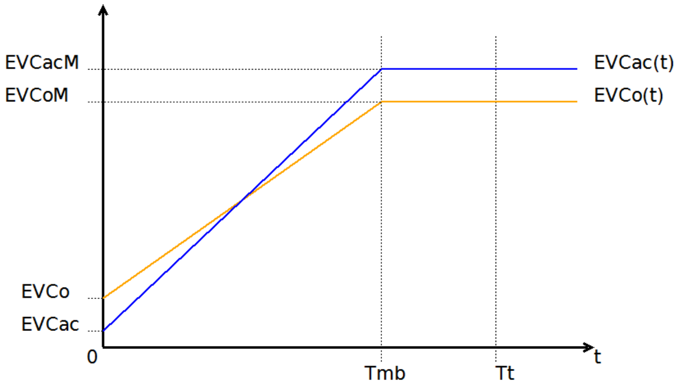

Fig. 3. Behaviors of the detection certainties for acoustic and optical methods.

Regarding localization, both optical and acoustic methods are very accurate for determining position of the leak. The simulated scenario contemplates the leak location may vary according to a normal distribution with mean L_{ac} and standard deviation $L_{ac}R$, these data are provided as simulation parameters. Uncertainty remains constant throughout the simulated scenario with a value DL_{ac}. Fig. 4 shows the scheme described above for acoustic method, the same behavior is proposed for the optical method. However, localization behaviors can be modified depending on the characteristics of the proposed methods.

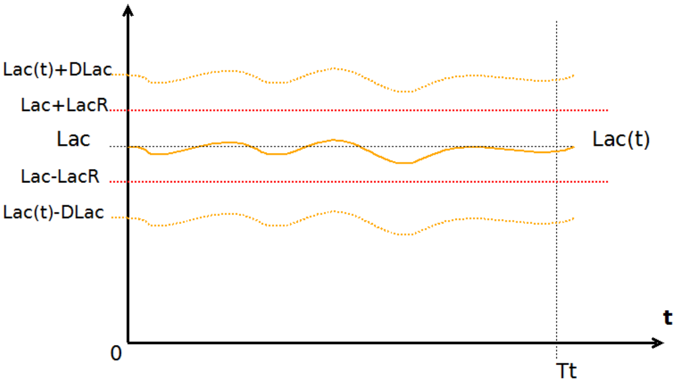

Fig. 4. The location for the acoustic method $L_{ac}(t)$ varies according to a normal distribution in time, with mean L_{ac} and deviation $L_{ac}R$. Uncertainty remains constant at the value DL_{ac}.

According to Table 2, the mass balance method not only provides the certainty of the event and the location ($EVC_{mb}(t)$, $L_{mb}(t)$ and $DL_{mb}(t)$), it also includes the amount of leaked product together with its uncertainty. As in optical and acoustic methods, we assume that the uncertainty will increase linearly with the amount of leaked product. Fig. 5 shows the proposed behavior for $EVC_{mb}(t)$, note that this starts at the instant that the leak T_{mb} has occurred, reaching the maximum value $T_{mb}M$, from which the leak is maintained at a constant value.

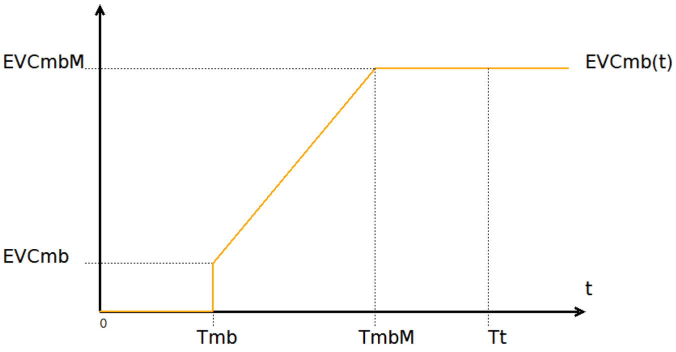

Fig. 5. $EVC_{mb}(t)$ behavior. Note that $EVC_{mb}(t)$ increases linearly at the beginning of the leak, from a value EVC_{mb} to a maximum value $EVC_{mb}M$ at the time $T_{bm}M$, where we assume that the leak has stabilized.

However, the amount of leaked product does not have to increase linearly, possibly be monotonically increasing with logarithmic increasing until reaching a maximum, as proposed in Fig. 6. As seen in Fig. 6, at the moment that the leak occurs, it begins with a value PL_{mb}, and after a while stabilizes to a value $PL_{mb}M$. Note that the mass balance method depends on the amount of leaked product; however, we will consider the uncertainty $DPL_{mb}(t)$ has a behavior according to a normal distribution with mean DPL_{bm} and standard deviation $DDPL_{mb}$.

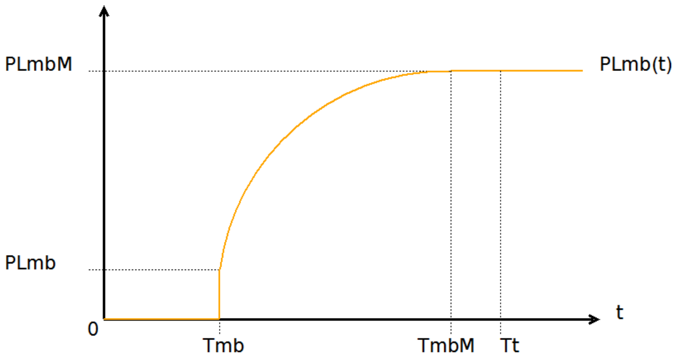

Fig. 6. Behavior of the amount of leaked product $PL_{mb}(t)$.

The location of the leak in the mass balance method is not as accurate as in acoustic and optical methods. Therefore, it is considered that this parameter may vary according to a uniform distribution over a range centered L_{mb}, as shown in Fig. 7. As in the other two detection methods, localization uncertainty remains constant.

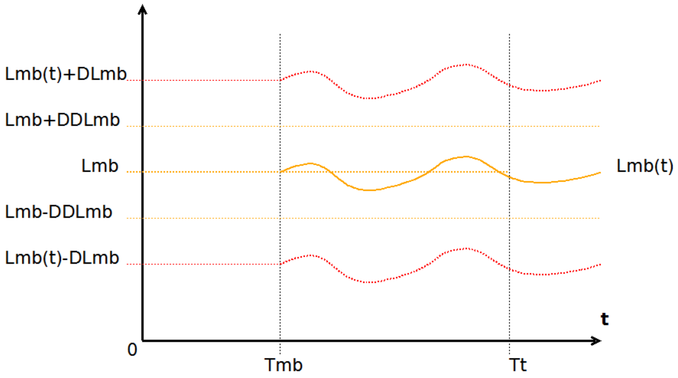

Fig. 7. Behavior of the leak location for the mass balance method.

The parameter values for the simulated scenario previously described are listed in Tabla 3.

V. RESULTS AND DISCUSSION

Fig. 8 to Fig. 11 show the results of the simulated scenario, according to the data given in Table 3. Fig. 8 illustrates the behavior of the location for each location and detection method described above. Note that there are points which are not correlated, which would allow determine the effect of variations in the parameter of the event localization by the data of the collaborative system to detect and locate leaks.

Leak location provided by the collaborative system is shown in Fig. 9. Note the transient time before 30 as a result of differences in location between the optical and acoustic methods. However, once the mass balance method is in operation, the location is stabilized at the proposed value of 100 km (see Table III).

TABLE III. THE PARAMETER VALUES FOR THE SIMULATED SCENARIO

Simulation parameter	**Detection method**		
	Mass balance	***Acoustic***	***Optical***
Event certainty	Minimun value $EVC_{mb} = 5$ Maximun value $EVC_{mb}M = 100$	Minimun value $EVC_{ac} = 5$ Maximun value $EVC_{ac}M = 95$	Minimun value $EVC_{o} = 20$ Maximun value $EVC_{o}M = 80$
Event location	Average $L_{mb} = 100$ Deviation $DDL_{mb} = 10$ Uncertainty $DL_{ac} = 30$	Average $L_{ac} = 100$ Deviation $L_{ac}R = 20$ Uncertainty $DL_{ac} = 10$	Average $L_{o} = 100$ Deviation $L_{o}R = 10$ Uncertainty $DL_{o} = 5$
Amount of leaked product	Minimum value: $PL_{mb} = 5$ Maximum value: $PL_{mb}M = 40$ Uncertainty Average $DPL_{mb} = 8$ Deviation $DesDL_{mb} = 2$	n/a	n/a

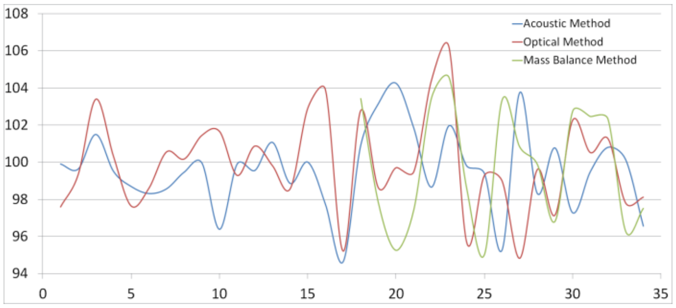

Fig. 8. *Leak location* behavior in kilometers for each detection and localization method. The *x* axis represents the number of messages generated by the leak event.

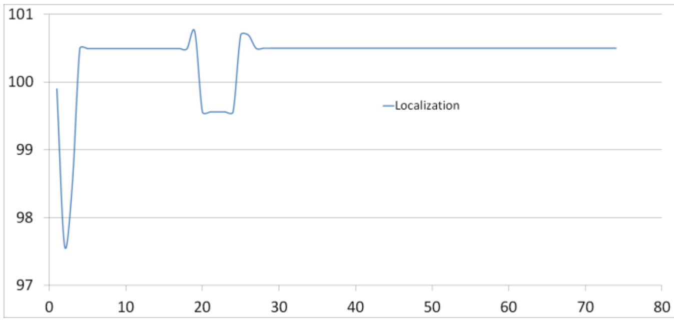

Fig. 9. Evolution of *leak location* parameter.

Fig. 10 shows the evolution of leak scenario in terms of the three levels of detection mentioned in Section 3, i.e., prevention, alarm and leak. These levels are quantized such that the prevention level corresponds to range [0, 1], the alarm level to range [1, 2] and finally leak level to range [2, 3]. The simulated scenario goes through all the levels described above, and the leak is confirmed from the time 30, when the mass balance method is in operation. The latter can be seen in Fig. 11, wherein the level of leak per time unit is presented.

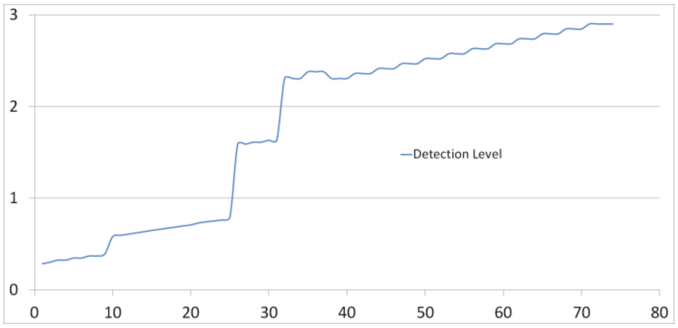

Fig. 10. Leak detection levels. The intensity of each level depends on the accuracy of the detected event, where a value greater than 2 indicates a possible leak.

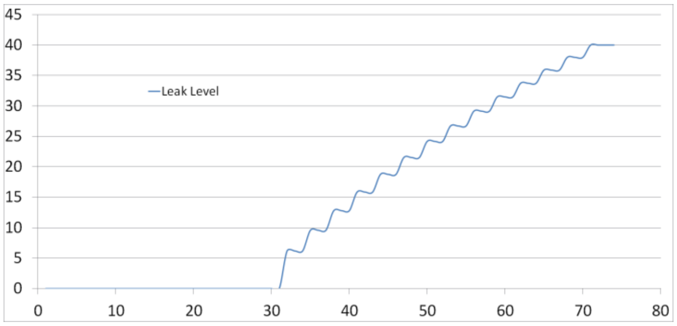

Fig. 11. Magnitude of the leak on time. Measurement units for the *y* axis correspond to the leak volume per unit time, while the *x* axis represents time.

VI. CONCLUSIONS

Computer simulations have become a useful tool for estimating and testing the performance of computational solutions to engineering problems. In this paper we have presented a novel leak event simulator in pipelines and shown its helpfulness in generating input data for a collaborative system for leak detection. The simulator was able to produce different scenarios with data generated from probability distributions. Thus, the behavior of collaborative system for leak detection was evaluated and necessary adjustments to improve performance were carried out.

ACKNOWLEDGMENT

The authors would like to thank Andriy Sadovnychyy, Daniel González González, Kevin Jonathan Gómez Elorza and Juan Luis Peña Falcón for making a valuable contribution to this project.

REFERENCES

[1] TRB - Transportation Research Board, “Transmission Pipelines and Land Use A Risk-Informed Approach,” 2004. [Online]. Available: http://onlinepubs.trb.org/onlinepubs/sr/sr281.pdf.

[2] Murvay, P.S. and Silea, I., “A survey on gas leak detection and localization techniques,” J. Loss Prev. Process Ind., vol. 25, pp. 966–973, 2012.

[3] EGIC, “7th EGIC-report 1970-2007 gas pipeline incidents,” 2008. [Online]. Available: http://www.egig.eu/uploads/bestanden/d1244d38-8194-46e8-89f4-6b6258d05f3a.

[4] Laurentys, C.A., Bomfim, C.H.M., Menezes, B.R., and Caminhas, W.M., “Design of a pipeline leakage detection using expert system: A novel approach,” Appl. Soft Comput., vol. 11, pp. 1057–1066, 2011.

[5] da Silva, H.V., Morooka, C.K, Guilherme, I.R., da Fonseca, T.C., and Mendes, J.R.P., “Leak detection in petroleum pipelines using a fuzzy system,” J. Pet. Sci. Eng., vol. 49, no. 2005, pp. 223– 238.

[6] Barradas, I., Garza, L.E., Morales-Menendez, R., and Vargas-Mart´ınez, A., “Leaks Detection in a Pipeline Using Artificial Neural Networks,” presented at the CIARP 2009, 2009, vol. 5856, pp. 637–644.

[7] Belsito, S., Lombardi, P., Andreussi, P., and Banerjee, S., “Leak Detection in Liquefied Gas Pipelines by Artificial Neural Networks,” Aiche J., vol. 44, no. 12, pp. 2675–2688, 1998.

[8] Xu, D.L., Liu, J., Yang, J.B., Liu, G.P, Wang, J., Jenkinson, I., and Ren, J., “Inference and learning methodology of belief-rule-based expert system for pipeline leak detection,” Expert Syst. Appl., vol. 32, pp. 103–113, 2007.

[9] Yon, M., Leonard, R., and Shoop, A., “Leak detection: Technology catches up to theory.,” Control Eng., vol. 56, no. 10, pp. 16–17, 2009.

[10] Zhou, Z.J, Hu, C.H., Yang, J.B., Xu, D.L., and Zhou, D.H., “Online updating belief rule based system for pipeline leak detection under expert intervention,” Expert Syst. Appl., vol. 36, pp. 7700–7709, 2009.

[11] K. Fukushima, Maeshima, R., A. Kinoshita, Shiraishi, H., and I. Koshijima, “Gas pipeline leak detection system using the online simulation method,” Comp Chem Engng, vol. 24, pp. 453–456, 2000.

[12] Liu, A.E., “Overview: Pipeline Accounting and Leak Detection by Mass Balance, Theory and Hardware Implementation.” Quantum Dynamics, INC., 2008.

[13] Doorhy, J., “Real-Time Pipeline Leak Detection And Location Using Volume Balancing,” Pipeline Gas J., vol. 238, no. 2, pp. 65–67, 2011.

[14] Geiger, G., “Leak Detection and Locating – A Survey,” 2003. [Online]. Available: http://www.psig.org/Papers/2000/0301.pdf.

[15] Miller Ronnie, K. and McIntire, P., Nondestructive Testing Handbook, 2nd ed., vol. 5. ASNT, 1987.

[16] Meng, L., Yuxing, L., Wuchang, W., and Juntao, F., “Experimental study on leak detection and location for gas pipeline based on acoustic method,” J. Loss Prev. Process Ind., vol. 25, pp. 90–102, 2012.

[17] Streicher, V.J., “Acoustic monitoring systems - System concept and field experience,” Nucl. Eng. Des., vol. 129 (1991), pp. 151–162, 1991.

[18] Tanimola, F. and Hill, D., “Distributed fibre optic sensors for pipeline protection,” J. Nat. Gas Sci. Eng., vol. 1, pp. 134–143, 2009.

[19] Ben-Mansour, R., Habib, M.A., Khalifa, A., Youcef-Toumi, K., and Chatzigeorgiou, D., “Computational fluid dynamic simulation of small leaks in water pipelines for direct leak pressure transduction,” Comput. Fluids, vol. 57(2012), pp. 110–123, 2012.

[20] Sun, L., “Mathematical modeling of the flow in a pipeline with a leak,” Math. Comput. Simul., vol. 82(2012), pp. 2253–2267, 2012.

[21] Kim, M.S. and Lee, S.K., “Detection of leak acoustic signal in buried gas pipe based on the time–frequency analysis,” J. Loss Prev. Process Ind., vol. 22(2009), pp. 990–994, 2009.

[22] Brodetsky, I. and Savic, M., “Leak Monitoring Systems for Gas Pipelines,” presented at the IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP-93), Minneapolis, MN, USA, 1993, vol. 3, pp. 17–20.

[23] Qingqing, X., Laibin, Z., and Wei, L., “Acoustic detection technology for gas pipeline leakage,” Process Saf. Environ. Prot., vol. 91, pp. 253–261, 2013.

[24] Mishra, A. and Soni, A., “Leakage Detection using Fibre Optics Distributed Temperature Sensing,” presented at the 6th Pipeline Technology Conference 2011, Hannover Messe, Hannover, Germany, 2011.

[25] Rajeev, P., Kodikara, J., Chiu, W.K., and Kuen, T., “Distributed Optical Fibre Sensors and Their Applications in Pipeline Monitoring,” Key Eng. Mater., vol. Vol. 558 (2013), pp. 424–434, 2013.

[26] Huang, S.C., Lin, W.W., Meng-Tsan Tsai, M.T., and Chen, M.H., “Fiber optic in-line distributed sensor for detection and localization of the pipeline leaks,” Sensors Actuators, vol. 135 (2007), pp. 570–579, 2007.

[27] Fu, Q., Wan, H., and Qiu, F., “Pipeline Leak Detection based on Fiber Optic Early-Warning System,” Procedia Eng., vol. 7(2010), pp. 88–93, 2010.