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Inherent Safety Index For Transportation Of Chemicals

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ABSTRACT

Inherent Safety can be understood as the absence or reduction of hazards (which implies lower risk) rather than low risk reached by add-on protective barriers. While the methodologies for risk analysis are well developed and understood, the evaluation of inherent safety is still not based on systematic procedures and depends on the assessment of subjective principles. The behavior of a chemical substance is one of the most important sources of hazard in a chemical process due to its intrinsic chemical and thermodynamic properties. When these substances are raw materials or sub-products (waste) they must be transported to/from the chemical facility, and this activity extends the chemical hazards from the processing plant to the community. Therefore, to obtain a general evaluation of the inherent safety level of a chemical plant, it is necessary to consider the hazards due to transportation of chemicals and treat these as an additional "property" of the substance.

This paper presents an overview of a novel inherent safety index based on fuzzy logic, which is useful to evaluate the inherent safety level of a plant. An example evaluates the transportation step of chemical substances, shows how the index works, and describes how it can be applied to different stages of the life cycles of a chemical facility. In this paper a very brief and basic introduction to fuzzy logic mathematics is provided. More information and related internet links can be obtained from the website mkopsc.tamu.edu and then from the links research → inherent safety → fuzzy logic.

Keywords: inherent safety, risk analysis, chemical transportation, fuzzy logic

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INTRODUCTION

Transportation of chemical raw materials and chemical products plays a very important role in the analysis of the inherent safety level of a chemical plant. Transportation and inherent safety share also the common problems of data uncertainty, complexity due to the many factors that should be analyzed, subjectivity, and lack of a quantification methodology. The mathematical approach proposed in this paper is based on the fuzzy set theory rather than probability and statistics.

The first part of the paper explains the relation between transportation and inherent safety, provides a brief introduction to fuzzy logic, and explains why it is a better tool than statistical methods to analyze inherent safety and transportation. The second part of the paper describes how to use the proposed fuzzy logic approach and presents an example.

TRANSPORTATION AS AN ELEMENT OF INHERENT SAFETY

Inherent safety is based on the elimination of hazards rather than control of them. This main idea has been recognized as a good and powerful approach to increase the safety level of a chemical plant. During the last years several papers have been published on the application of inherent safety describing advantages and disadvantages of this approach compared to the traditional safety approach (controlling hazards by using layer of protection and other risk reduction measures), and several analytical tools have been proposed. However, in spite of all the effort, the application of inherent safety faces resistance do to the lack of a systematic quantification tool and the difficulties of application to an operating plant. Another common misconception about inherent safety is that it conflicts with environmental measures. These factors contribute to the idea that inherent safety is a collection of good ideas with little practical importance.

When an industry is forced to move towards an inherently safer approach, it is possible to interpret the principles in a way that will impact other related aspects of safety. For instance, one of the easier ways to improve the inherent safety level is to reduce the inventory of hazardous chemical substances. However, if this step causes an increase the frequency of shipments of chemicals to or from the plant, the overall effect could be an increased transportation hazard. This example shows why transportation must be part of the inherent safety analysis of the plant and cannot be studied as a separate entity.

During the earlier stages of plant design, it is possible to choose safer chemicals to obtain an inherently safer plant. However, the idea of “safer chemical” should be based not only on toxicity, reactivity, or flammability aspects but also on volumes and transportation aspects. For instance, if two chemicals could be used, one required in small quantities and supplied from a close site but with hazardous toxicity and reactive properties, the other one with more benign properties but required in large quantities and supplied from a plant located far away, the question would be: “Which is the safest chemical?” Because the selection of the raw material can impact the processing conditions, the layout, and the type of commodities required, the answer to the question should be given based on the analysis of the entire process. However, the first step is the development of a procedure to analyze the properties as well as transportation characteristics.

Transportation of chemical substances is by itself an extremely complex and difficult topic, and when it is joined to the already complex issue of inherent safety quantification, the resultant problem could appear impossible to be solved. However no inherent safety quantification can be complete unless it takes into account the hazards related to transportation. The two questions that naturally appear here are:

1) How can transportation be included within inherent safety?
2) How to deal with all the complexity, uncertainty and imprecision common to both inherent safety and transportation?

Traditionally the hazards related to a specific chemical are health hazards (based on properties such as acute and chronic toxicity) and fire and explosion hazards (based on properties such flammability, explosivity, and reactivity). These hazards are rated by using indices (e.g., NFPA ratings) based on chemical and thermodynamics properties.

Following a similar approach, transportation hazards could be analyzed based on specific aspects such as mode of transportation, length of the route, and type of urban/rural areas travelled through. The transportation hazard then can be rated by a "transportation index", which could be used as an additional property of the specific chemical substance during the selection of the "safest chemical". Since each transportation mode has a characteristic range of possible volumes (e.g., tanks trucks can transport less volume than a rail car) the number of trips per year is a function of the total required volume. The frequency of the shipments depends on the total volume of chemical required by the plant but also by the size of the storage tank. Because of this relation, the hazards posed by transportation are related to the hazards posed by the plant and then can be included within the inherent safety evaluation. This answers the first question.

The answer to the second question requires the understanding of the source and type of uncertainty. This is also required to justify the use of fuzzy logic rather than probability theory. Randomness occurs when a random event has several possible outcomes (e.g., casting a die on a flat surface) whose probabilities are known or unknown. Since the outcomes are not ambiguous, the experimentation can yield a probability distribution function of the outcomes. The source of uncertainty here is whether an event will or will not occur and it is addressed by the probability theory. When the outcome of the experiment cannot be properly observed (e.g., due to bad illumination), it is not possible to identify the face of the cast die) further experimentation is not useful to reduce the uncertainty. In this case, each of the possible outcomes has a different degree of truth. This type of uncertainty can be better described by fuzzy logic because it deals with the degree of truth that the outcome belongs to a specific category, but it does not include the likelihood of occurrence of an event (as probability does) [Lootsma F., 1997]. Another type of uncertainty, ambiguity, arises when a statement can be interpreted in different ways because it has different meanings depending on the context. For instance, chlorofluorocarbons (CFC) are safe gases compared to ammonia in terms of explosion hazards, however they destroy the ozone layer, so in terms of environmental hazards they are not safe. Here the word "safe" is an ambiguous concept that depends on the context of the analysis.

The two different approaches can be described by the example of the glass of water half-full or half-empty. If we want to know the probability of the glass being classified as full or empty we have only two categories, and the uncertainty of the probabilistic approach is related to the presence or absence of that element in one of the two categories. In fuzzy logic, the two categories overlap each other, and the uncertainty is related to the degree of membership in each one of the two categories, as described in Figure 1.

The advantage of the fuzzy logic approach is more evident in the following example. If we have an empty glass it is easy to classify it under the Boolean set "empty". However, if we transfer a few drops of liquid to the glass, it is no longer empty (however the state of emptiness could be approximated), and under the probabilistic approach (Boolean sets) the almost-empty glass does not belong to any of the two sets (fully-empty or fully-full). The fuzzy logic approach can handle this case by assigning a lower membership degree to the "full" set and a higher membership degree to the set "empty", which is illustrated in Figure 1.

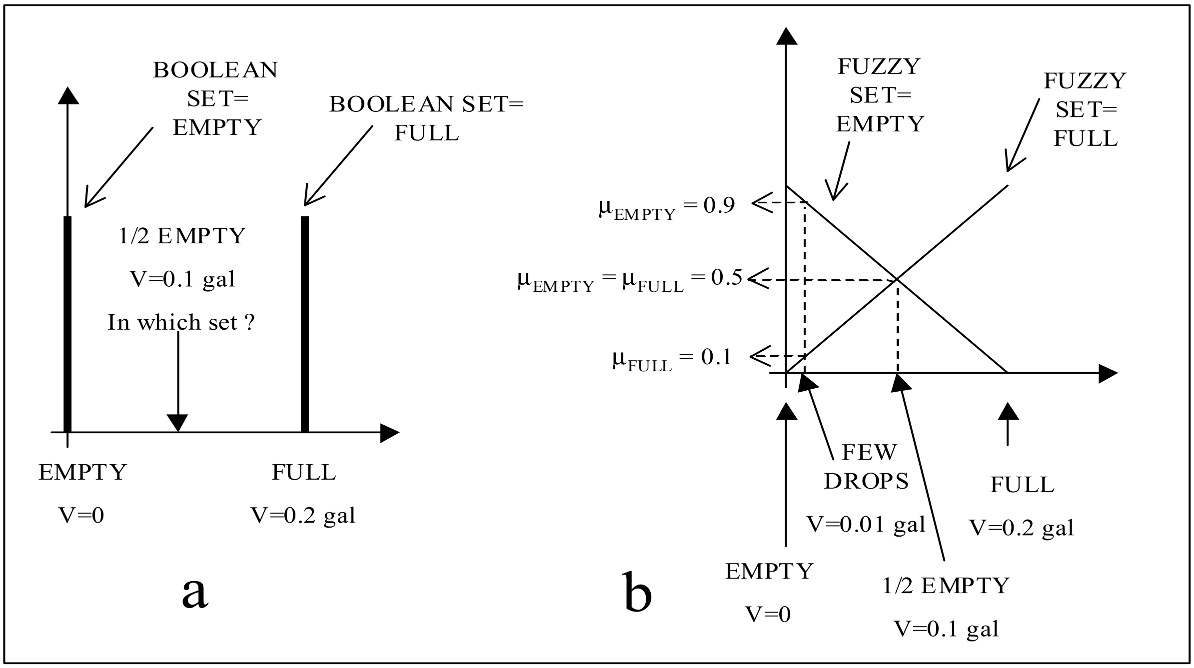

Figure 1: Boolean and fuzzy logic approaches for the "1/2 empty/full glass of water".

RISK and INHERENT SAFETY

Risk cannot be related to a unique type of uncertainty since every event can have several outcomes. The events cannot, however, be classified precisely into a small number of specific categories, and it is difficult to calculate their probabilities [Lootsma R., 1997]. Risk calculations are performed mainly using the probabilistic approach, and the effect of uncertainty on the calculation of rates and probabilities is recognized but not addressed. In some cases fuzzy logic has been used for risk assessment and fault tree analysis, and an interesting application of fuzzy logic to transportation risk assessment is presented by Bonvicini et al, 1998, where the authors treat the release frequency and rates as fuzzy numbers.

MATH Fundamentals of Fuzzy Logic

Fuzzy logic is based on the concept of fuzzy set that, contrary to a crisp or Boolean set, overlaps each other. An element can have partial membership in more than one fuzzy set while this is not allowed for Boolean sets. The degree of membership of each element into a fuzzy set is described by the membership function whose value varies between 0 and 1, where the value of 0 is assigned when the element does not belong to the specific fuzzy set. The membership function can have several shapes with triangular the most common. The base width of the membership function represents the uncertainty associated with the elements of the set [Duboise and Prade, 1983].

The fuzzy set for each variable is related to each other by using fuzzy IF-THEN rules that describes the knowledge about the relation existing between the two sets. Because each element can belong to more than one set at the time, several rules must be evaluated for each input, and the final answer takes into account the contribution of each fuzzy rule.

The proposed transportation index is based on nine fuzzy inference systems from the Mamdami [Yen and Langari, 1999] model, and the definition of the AND and OR operation is based on MIN and MAX operations, respectively [Zadeh L.A., 1999]. The software that was used for the calculations is the Fuzzy Logic Toolbox and Simulink from MATLAB.

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REVIEW OF THE INHERENT SAFETY INDEX FOR FIXED SITE

The inherent safety index based on fuzzy logic measures hazards related to the chemical substance, the process, and the equipment present in the plant. The process hazard evaluation takes into account processing conditions such as temperatures and pressures, materials required for the construction of the equipment, protective equipment for workers, and the degree of packing of the evaluated unit or plant. The hazards related to process equipment are related to the type of equipment and the volume and conditions of storage and process tanks. The storage tanks represent a large accumulation of chemical substances and usually they are also a significant source of hazards. Because of this, one of the easier ways to reduce the risk of the plant is by reduction of inventory. When the reduction of stored volumes implies a higher transportation frequency, it is necessary to evaluate the options to identify the safest option. When, during the design stage it is possible to choose between two or more chemicals, the consideration of the transportation factors into the analysis can help to select the best option.

Evaluation of the chemical substance is based on properties such as toxicity (based on the TLV), flammability (based on flash temperature), explosivity (based on the explosive limits), chemical interactions, and reactivity. The transportation index described in this paper should be used as an additional property of the chemical substances.

THE TRANSPORTATION PROBLEM

Introduction

Transportation is becoming every day more a major concern for the chemical industry especially after the events of 9/11 and lately with the controversy associated with the transportation of nuclear waste to Yucca Mountain. Transportation is also assumed to be required, but in some cases it can be avoided or reduced if the chemicals can be substituted, shipped under a different mode, or produced on site.

The typical transportation problem occurs when a plant A requires a certain chemical that can be shipped by different modes (e.g., truck or train) from different plants located at different distances. Each possible route goes through different environments (e.g., populated and rural areas) and consequently has a different risk. The problem is how to choose the best route and the best mode to reduce the hazards. The required storage tank in plant A varies according the frequency and volume of the shipments, and this dependency links transportation to inherent safety. Additional decisions can improve the inherent safety level of transportation by choosing the type of container and the conditions (e.g., pressure, temperature, concentration) that reduce the hazards [CCPS, 1996]. Refrigerated storage is usually safer than pressurized storage tanks, but if the total quantity of stored chemicals is small, as in transportation, the observation might not be true [Kletz, 1998]. Because the transportation problem is affected by many external and unpredictable variables, the selection of the conditions that minimize the risk represents also the inherently safer option.

When decisions have to be made, the typical questions asked are related to the associated risk. However, the problem is complex, and the answer is not easy to determine due to the lack of consensus on a systematic methodology (e.g., Soccomano (1993)).

Risk assessment for transportation is based on the typical risk definition:

RISK = f (Accident rate, Probability of release, Consequences)

The accident rate for transportation is mode specific (e.g., road, railroad, pipeline, barge, ship) but also depends on factors such as the environment (e.g., urban, rural, suburban, remote), contributing factors, and initiating events. The accident rate for trucks depends on the type of truck, the type of road, traffic, and velocity, among others. For railroads, the class of track is important, as well as the location (main track or yard), the number of intersections with roads and highways, among others.

The probability of release describes the likelihood of the tank to suffer a failure following the accident. It depends on the type of tank, the wall thickness, and the pressure of the tank but also on dynamics factors such as the velocity, the type and size of impacted object, the position where the tank of fittings are hit, the material and wall thickness of the tank, and the type of force (e.g., puncture, crush, fire).

The consequences of the accidents depend on several other factors such as the size and position of the hole, the geographical location of the car, the time of the day which affects the number of exposed people, the weather conditions that affect the dispersion modeling, and the direction of the release. The size of the hole in the railcar has been studied by Raj (1992) and the data are in some case inconclusive. The size of the hole affects directly the release rate of the chemical but also the position is important. If the hole is in the vapor space the release rate is lower, however the vapor space is not always at the top of the car because this can be overturned.

The combination of all the factors produces a large number of possible releasing scenarios. Additionally, the accident can happen along the selected route in any location, each one characterized by different weather conditions, socioeconomic, and terrain characteristics. Because of all these possible variations, the transportation problem is not so well defined as in the case of a fixed facility. Another factors in the analysis of transportation risk is the presence of accidents characterized by high consequences but low frequency [Brown D.F. 2000].

How to present and analyze the risk is another problem for transportation. The individual risk at any specific location is given by the sum of the contributions of each scenario. While individual risk does not depend on the length of type of the route and is normally very low, societal risk depends on the length of the route and could be potentially unacceptable due to the additive effects along the route (Rhyne, 1994).

Data problem

Transportation risk assessment is based on the same principles as the fixed site procedure and relies on accident databases for the statistical data required to calculate accidents frequencies, release probabilities, and other parameters. However, these databases are not immune to the typical accident data collections such as underreporting (which is difficult to quantify), different reporting criteria, and various reporting parameters and scopes. Because of these problems, database accident data are difficult to compare. However, to develop a transportation analysis, data from several different databases must be used, and this requirement increases the uncertainty and complexity of the analysis. Additionally the required data must span several years during which regulation changes occurred and technical improvement of tank railcars and truck design occurred. The drop in accident rate for railroads during the last 20 years is a good example of this effect. The accident rate dropped from 15.8×10^{-6} accident/train mile in 1977 to $4.6\ 8 \times 10^{-6}$ accident/train mile in 1986. Since then it has been fluctuating around that value with a lowest rate of 4.3×10^{-6} accident/train mile in 1987 [FRA, 2000]. During 1980 the railroad tankcars design was modified with self-couplers and head shields that dramatically reduced risk of head puncture during an accident. In 1990 regulatory changes for transportation of toxic liquids reduced the likelihood of tank failures [Rhyne, 1994]. This and other regulatory changes contributed to the decreasing of accident rates and release probabilities, but their effect is not immediate and continues during several subsequent years.

Additional sources of uncertainties are related to the reporting of total number of mile traveled, quantities of transported substances, conditions before and during the accident, and detailed information on the construction of the tanks (such as material and wall thickness). Also the data problem is different for each mode of transportation. For railroad the collected data have a better quality and are more nearly complete with respect to data collected for truck and road transportation.

All these elements together show the complexities associated to the evaluation of the transportation problem. Several researches and methodologies have been proposed, but two of them are the most significant. Soccomano (1993) proposed an exercise where the same specified corridor was analyzed for two transportation modes (truck and railroad) by seven different academic, industrial, or consulting organizations. The goal was to compare the assumptions and results obtained by the seven groups. Each group developed the transportation risk analysis for the given corridor based on very different assumptions and different factors that yielded final results with great variability. For instance the accident rate used for road transportation varied between 0.31×10^{-6} and 2.6×10^{-6} accident/train mile.

The CCPS (1995) proposed a transportation risk assessment procedure based on a well-defined and systematic methodology for fixed site facility. However, when most of the expected important factors are taken into account (each one with several possible levels) the complexity of the problem is overwhelming and it becomes difficult to keep track of all the information used. Additionally, the lack of detailed and specific data for the development of the analysis contributes to the difficulty of applying the methodology.

MODEL DESCRIPTION

The model proposed here has the purpose to evaluate the hazards of truck transportation from a macroscopic approach given the fact that during the early stages of process design only fundamental transportation information is available and easy to get. The procedure is based on the general idea that three major components contribute to the transportation risk: accident frequency, release probability, and consequences. Each one of these components must be described by factors that are selected according to knowledge that can be extracted from the statistical information in the databases. Keeping in mind the uncertainty associated with the data, the lack of detailed information, the learning from the corridor exercise, and the problems of complexity for detailed analysis, the development of the transportation index was based on the following steps:

1) Analysis of information and data reported by several studies and literature sources.
2) Selection of the most important macro factors that appeared to be relevant to the specific component (accident rate, release probability or consequences) for which the information can be available during the early design stages.
3) Selection of the data used to extract the knowledge needed to design the membership functions, fuzzy relations, and fuzzy inference systems.
4) Design of fuzzy relations and fuzzy IF-THEN rules to model the behavior of the selected factors and its relations with respect other factors.

The three major components of the index depends on the following factors, and they are described by three fuzzy inference systems:

1) ACCIDENT RATE:
    a) Environment: rural or urban
    b) Type of road: highway, multilane divided, multilane undivided, two lanes, one-way

2) RELEASE PROBABILITY:
   a) Environment: rural or urban
   b) Type of road: freeway or non-freeway
   c) Type of truck: simple, single trailer, double trailer

3) CONSEQUENCES:
   a) Dispersion hazard: based on boiling point of the substance and transportation temperature
   b) Toxicity: based on the ERPG-2 of the chemical
   c) Flammability and explosivity: based on the NFPA ranking
   d) Volume transported by the truck (which depends on the type and configuration of the truck)

In order to generalize the model and including other important factors that can affect the components, the following correction factors are applied and they are described by three fuzzy inference systems:

1) ACCIDENT RATE: Correction due to the type of the truck
   a) Environment: rural or urban
   b) Type of road: highway, multilane divided, multilane undivided, two lanes, one-way
   c) Type of truck: simple, single trailer, double trailer

2) RELEASE PROBABILITY: Correction for wall thickness
   a) Design pressure of the tank

3) CONSEQUENCES: Correction for population concentration
   a) Number of people/mile^2

The final transportation hazard, TH, is calculated using the following formula:

$$TH_i = \{[(\text{ACCIDENT RATE})_i\ (\text{CORR. FACTOR1})_i]] * [(\text{RELEASE PROBABILITY})_i\ (\text{CORR. FACTOR2})] * [(\text{VOLUME})(\text{TOXIC INDEX})(\text{EXPLOSIVE/FLAMM. INDEX})(\text{CORR. FACTOR3})]\} * (\text{TOTAL NUMBER OF SHIPMENTS PER YEAR}) * (\text{MILES})i$$

$$TH = \Sigma\, TH_i$$

The total number of shipments per year is given by $N = V/\ x\ n\ v_{hw}$,where V is the total volume of the chemical required in one year, n is the number of trailers per shipment and v_{hw} is the volume of each trailer. The volume of the tank that must be refilled per shipment is given by $v = x\ n\ v_{hw}$, where x represents the number of trucks required to refill the tank. Adjustment factors are used to calculate N and x when the volumes V, v and v_{hw} yield fractional values for N and x.

The sub-index i represents the different combinations of factors along the route. It is assumed that the route can be divided in segments where the population density, the type of road, and type of environment are constant. The calculations must be performed for each one of the i uniform segments, and the results must be added to obtain the final value. The weather is a major component for assessment of the consequences of a release, but for the purposes of this study, the evaluation of the area covered by the cloud is based on the dispersion index explained below. Additional assumptions are the following:

a) The total hazard index is based on the total length of the route and the number of shipments required per year. The frequency of the shipment is affected by the following variables:
   1. total amount of chemical required by the plant during one year (V)
   2. volume of the storage tank (v)
   3. volume of tank truck (v_{hw})
   4. truck type (single truck or single trailer, double trailer)

b) The data used are based on the Harwood and Russell (1990) report and other data reported by Rhyne (1994) and CCPS (1993). The purpose of the present paper is the development and test of an index to evaluate transportation hazards to be used by the inherent safety index. The limitations and uncertainties associates to the used data are recognized, but the analysis of accuracy and goodness of the data is beyond the scope of this paper.

The factors selected for the transportation index are described next. For the Accident Rate and the Consequences evaluation, the fuzzy sets and the fuzzy rules used are presented.

Release Probability

Truck accident can happen as a consequence of several factors or combination of factors. Harwood and Russell (1990) and Karlaftis and Golias (2002) reported lists of possible factors. In general they include the truck configuration, including its size and weight, truck operation, including cargo type and human factors associated with the driver, highway or road type, type of environment and geographical location, weather, and temporal factors such as time, day and month. Intuitively any of these factors can have an effect on the accident rate of a truck, however, as pointed out in both studies, the statistical data show that some of them, such as the weather condition, apparently does not affect the accident rate. Other factors, such as environment, road geometry and traffic volumes have been recognized by both studies to have a strong effect on the accident rate. This conclusion is reached by the two studies although they used different sets of data: Karlaftis and Golias (2002) used the Road Inventory database from the Indiana Department of Transportation (INDOT) and the Accident Information Record from the Indiana State Police for the years 1991 to 1995. These data are for any type of vehicular accidents. Harwood and Russell (1990) used the FHWA Office of Motor Carriers for the Sates of Michigan, Illinois, and California for the years 1984-1985, and these data are for truck accidents.

The common conclusion and the additional analysis presented by Harwood and Russell (1990) indicates that these three parameters are the most important to describe the accident frequency for trucks. For the purpose of this paper, the data presented by Harwood are used here because it reports the accident frequency for the three states based on type of environment and type of roadway.

The type of environment is classified into urban or rural according the expected population concentration. This is also an indirect measure of the expected traffic (heavier in urban environments) and the possibility of accidents due to vehicular impact. The road type is classified into highway, multilane divided and undivided, and two-lanes. It is expected that the accident rate decreases to the degree that the type of road is similar to a highway.

The type of environment is described by a scale from 0 to 10, while the type of road is described by a scale from 1 to 5. The accident frequency is described by a scale from 0 to 16, and it represents the accident frequencies multiplied by a factor of 10^6. The fuzzy sets are shown in Figure 2:

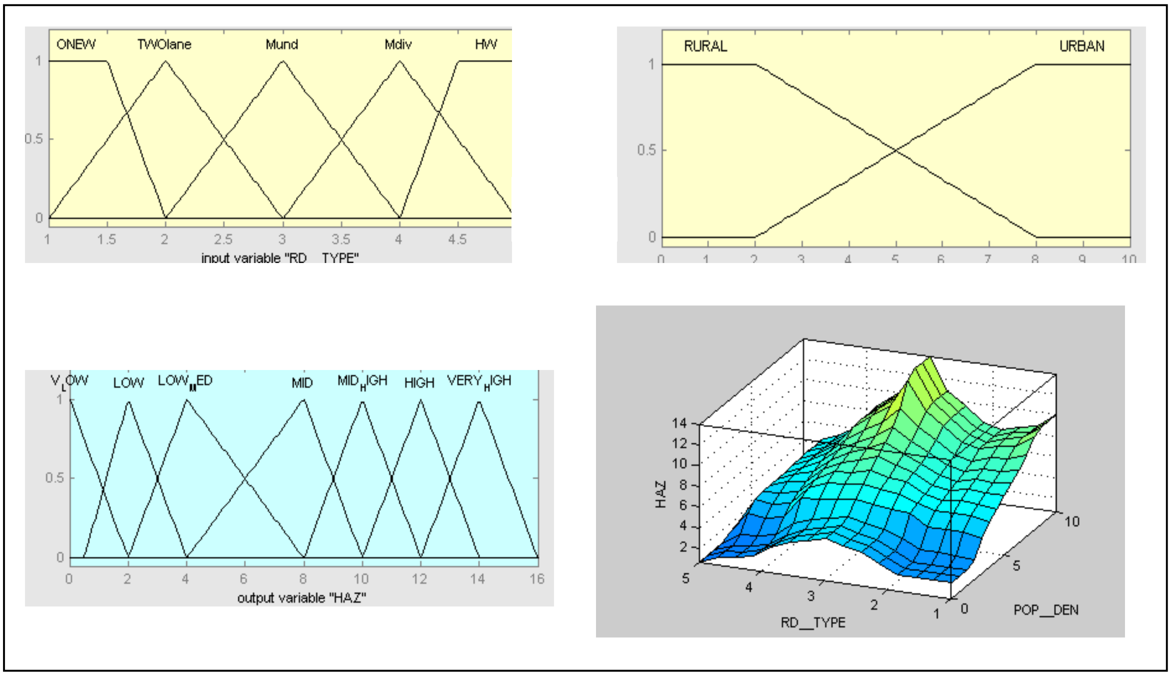


Figure 2: Fuzzy sets for the inputs "Type of road" (A) and "Type on environment" (B), and for the output "Accident frequency" (C). Defuzzyfied output surface (D).

Table 1 presents the data used and reports the fuzzy set classification used to develop the fuzzy rules, reported in Table 2:

Table 1: Accident frequencies as reported by Rhyne (1994) based on Harwood (1990) data from the averages for California, Illinois, and Michigan.

AREA TYPE	ROAD TYPE	ACCIDENT RATE Accident/mi	FUZZY SET
RURAL	TWO-LANE	2.19E-06	low
RURAL	MULTILANE UNDIVIDED	4.49E-06	med-low
RURAL	MULTILANE DIVIDED	2.15E-06	low

RURAL	FREWAY	6.40E-07	v-low
URBAN	TWO-LANE	8.66E-06	mid
URBAN	MULTILANE UNDIVIDED	1.39E-05	v-high
URBAN	MULTILANE DIVIDED	7.47E-06	MID
URBAN	FREWAY	2.18E-06	low
URBAN	ONE-WAY STREET	9.70E-06	mid-high

Table 2: Definition of fuzzy rules that express the knowledge extracted from the data in Table 1.

AC. RATE	**AREA TYPE**	
ROAD TYPE	URBAN	RURAL
TWO-LANE	MID	LOW
MULTILANE UNDIVIDED	VERY_HIGH	LOW_MID
MULTILANE DIVIDED	MID	LOW
FREWAY	LOW	V_LOW
ONE-WAY STREET	MID_HIGH	LOW

Correction due to type of truck

As reported by Harwood (1990) the type of truck and its configuration can affect the accident rate. The trucks can be classified as:

Simple: unit consisting of the cargo compartment mounted on the same rigid frame as the cab. These trucks are smaller compared with the other two types and are used for short-range routes.
Single trailer: consists of a tractor and a separate single trailer.
Double trailer: consists of a tractor and two separate trailers.

Because of the different design and dimensions, these three trucks present different driving problems. Large trucks are affected by the geometry of the roads such as curves, horizontal and vertical alignment, interchange ramps, shoulders, and railroad crossing (Harwood and Russell, 1990). The truck configuration is a parameter that should be taken into account during the design stage to optimize the size of the tank and the transportation hazards.

The data reported by Harwood and based on a study developed by the California Department of Transportation for the years 1979 to 1983 are useful for developing a fuzzy relation between the type of environment (rural or urban), the type of road (freeway or non-freeway), and the type of truck (simple, single trailer or double trailer). The data indicate that the accident rates are generally higher on non-freeways in urban areas.

This information can be used to modify the accident rate according the expected type of truck and the route environment. The values for "all trucks" is taken as an average from which deviations occurs according to the case. The percentage of deviation is used for designing the fuzzy relation that describes how much the accident rate should be affected. The maximum increased/decreased allowed is 50%.

Release probability

Because of the accident, the tank-truck can suffer different type of damages depending on several factors such as the velocity, dynamics of the accident, type of force and type of terrain that can cause the overturn of the truck or not. A detailed analysis of all several factors is proposed by Rhyne (1994) based on reports and studies presented by other researchers.

The velocity is the most important factor related to release probability along with the thickness of the wall of the tank. The velocity can be related to the type of road by a fuzzy relation developed using the data presented by Rhyne (1994) and is based on Harwood and Russell (1990). An additional advantage of this set of data is that it is directly related to the set of data used for the accident rate model.

Correction due to thickness of the wall

The analysis of data developed for railroad accidents clearly suggests that the increased thickness of the head of the tanks acting as shields decreased the incidence of tank-car punctures during an accident (Raj P.K. and Turner C.K., 1993). Additionally, the internal pressure of the tank can reduce the tank's resistance to puncture (Phillips E.A. and Olson L.L., 1986). Similar information is not available for tank-trucks, however it can be inferred that as the tank is designed for higher pressures, the wall thickness should increase. Based on this, the classification of tanks presented by CCPS (1995) and based on the specific regulations is used here to develop a fuzzy relation based on internal pressure of the tank and the possible effect on the puncture resistance. This fuzzy relation is based only on knowledge, since no data are available to relate these variables and the material tensile strength. The relation is then used to modify (up to 50%) the release probability calculated with the relative fuzzy relation.

Tank volume

The volume of the tank is a direct measure of the amount of chemical transported by the truck (assuming it is full) and it affects the hazard of a release, since larger volumes represent longer leaking times and population exposure. This fuzzy variable is designed based on the data presented by CCPS (1995). It is assumed that the volume of the tank can range from 2,000 to 45,000 gal, and this range is transformed by taking the natural logarithm to maintain a good representation of the smaller volumes.

Toxicity index

The fuzzy relation describing the toxicity index is based on the ERPG-2 value of the chemical substances. The chosen scale ranges from a concentration lower than 1 ppm (i.e. Phosgene) to concentrations of 500 ppm. The range of the linguistic variable "toxicity" is transformed by taking the natural logarithm of the ERPG-2 range to achieve a good differentiation of the fuzzy sets for the lower (and most toxic) concentrations.

Explosivity and flammability indices

These two properties of the chemicals substances are described by using the NFPA ratings [NFPA 704, 2002]. The fuzzy variable here describes the hazards associated with the flammability and explosivity of the chemical. The linguistic variable here has a range between 0 and 32 and the input is given by the sum of the squares of the two NFPA indices. The square of the index (that varies between 0 and 4) acts as a penalty for the higher scores.

Dispersion hazard index

This factor is usually modeled with source and dispersion models for a selected wind speed and atmospheric stability. These models require not only the availability of specialized software but also the data regarding the weather conditions for each point on the expected route. This is a time consuming step that here is avoided by using the general knowledge on behavior of liquids and gases:

1) The boiling point (Tb) of a substance indicates its phase at normal conditions and how easily it will evaporate/condense when released at conditions different from the atmospheric temperature and pressure. This behavior here is described by $\Delta t1=25-Tb$. When $\Delta t1$ is large the substance will tend to evaporate faster and cover a larger area than a less volatile substance. The range for $\Delta t1$ is [-100, 100] and it is divided into five fuzzy sets, as shown in Table 3.

2) The tank temperature (Tt) indicates the condition at which the chemical is shipped (i.e., pressurized or refrigerated). This is described by $\Delta t2=25-Tt$ and it is assumed that when $\Delta t2$ is large the tank is refrigerated and when it is small the tank is pressurized. As noted by Kletz (1998) a refrigerated tank tends to be inherently safer than a pressurized tank because the substance is at low temperature and its vaporization will be slower due to the absorption of heat required to reach the boiling temperature. Additionally, for a pressurized tank the release rate will be larger than a refrigerated tank due to the higher pressure difference with respect the atmospheric pressure, so is expected that the area covered by the dispersion plume increases as the tank pressures increases. The range for $\Delta t2$ is [-100, 100], and it is divided into five fuzzy sets, as shown in Table 3.

Table 3: Definition of fuzzy rules that express the hazard as a function of the expected area covered by a dispersion plume under steady state conditions.

DISPERSION	**$\Delta t2=25-Tt$**				
$\Delta t1=25-Tb$	VERY LOW	LOW	0	HIGH	VERY HIGH
VERY LOW	MEDIUM	MEDIUM	LOW	VERY LOW	VERY LOW
LOW	HIGH	MEDIUM	LOW	VERY LOW	VERY LOW
0	HIGH	MEDIUM	LOW	VERY	VERY

				LOW	LOW
HIGH	VERY HIGH	HIGH	MEDIUM	LOW	LOW
VERY HIGH	VERY HIGH	VERY HIGH	HIGH	MEDIUM	MEDIUM

Figure 3 shows the resultant defuzzified surface that describes the expected hazard proportional to the size of the dispersion plume:

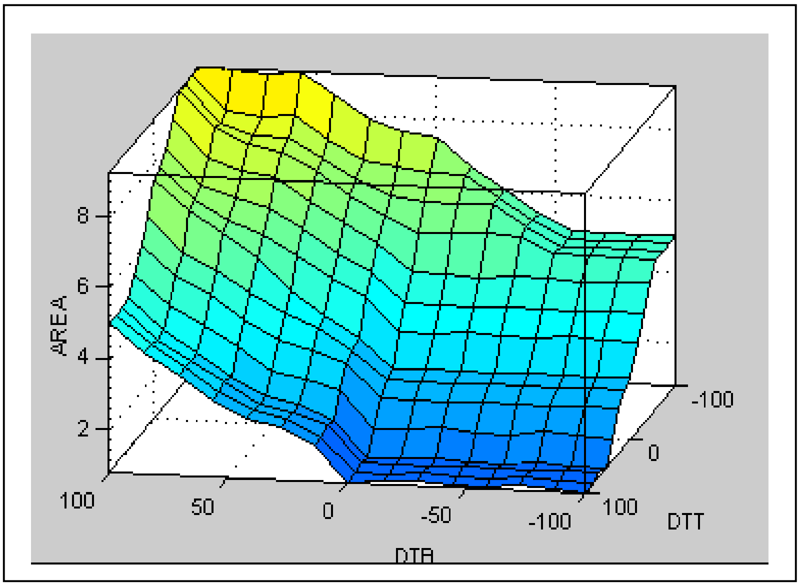


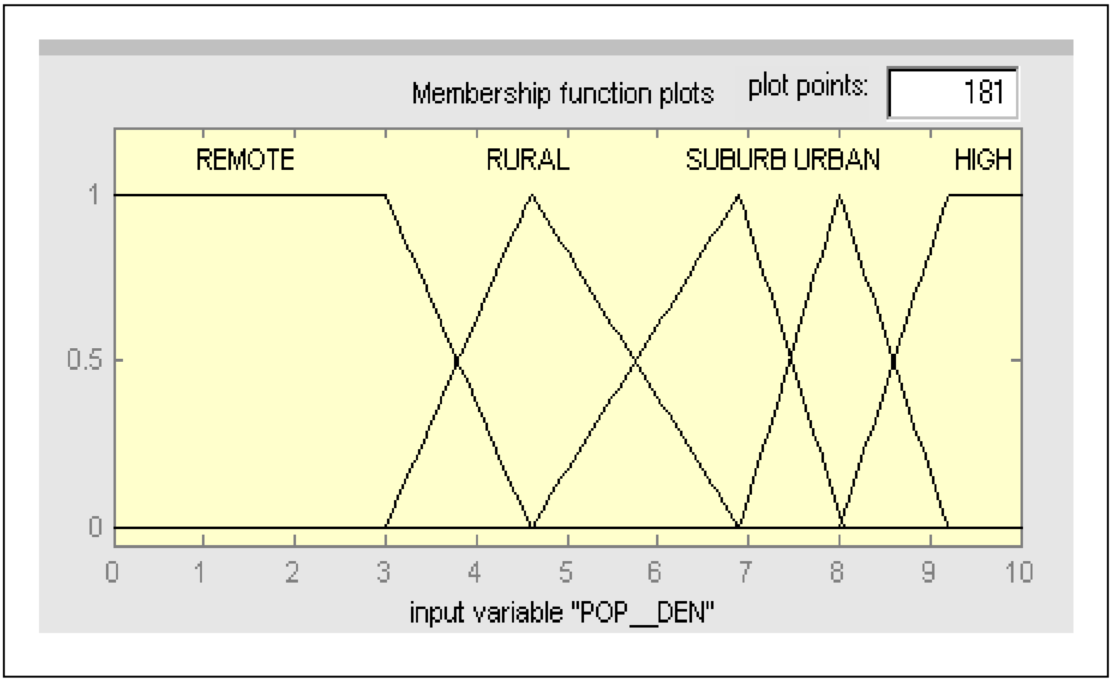
Figure 3: Defuzzyfied output surface for the inputs “Δt2=25-Tb” and “Δt2=25-Tt”

Correction for population density

The consequences and hazards of the plume dispersion are related to the density of the population present in the area of the release. Therefore, the dispersion index must be corrected for the expected population density. The location of the population and the variation in density are neglected during the daytime. This correction factor is based on the idea that as the population density increases the hazards of highly negative consequence increases too. The fuzzy sets, shown in Figure 4, describing the population density are based on the classification, displayed in Table 4, used by the United States Census 2000 [Census, 2000] and are more detailed than the sets used to model the accident rate to provide more sensitivity to the correction factor.

Table 4: Definition of fuzzy set for population density as a correction factor for the dispersion index.

CATEGORY	DENSITY [people/mi^2]	SCALED DENSITY Ln[people/mi^2]
REMOTE	20	3.0
RURAL	100	4.6
SUBURBAN	1,000	6.9
URBAN	3,000	8.0
EXTREMELY HIGH	10,000	9.2



plot points: 181

Figure 4: Fuzzy sets describing the population density from the data in Table 4.

RESULTS and DISCUSSION

The fuzzy logic methodology described in this paper has been applied to three fictitious routes with different lengths and classifications that are reported in Table 5. Each route is divided into segments (i) with constant population density, type, and condition of the road. It is expected that this type of information can be easily obtained from the Census data and GIS (Geographic Information System) software.

The index for population density (expressed as ln(people/mi^2)) is used as input in Figure 2A, while the index for type of road is used as input in Figure 2B. The index for type of road can be increased or decreased according the expected condition that is evaluated subjectively.

Table 5: Description of the three routes used as example

ROUTE	ENVIRONMENT	POP. DENSITY Ln (people/mi^2)	LENGTH mi	TYPE ROAD	ROAD CONDITION	
1	REMOTE	**3**	**100**	TWO LANES	Good condition	2.5
	RURAL	**5**	**50**	MUND	Bad condition	2.8
	SUBURBAN	**7**	**20**	MDIV	Many intersections	3.8
	URBAN	**9**	**20**	MDIV	Very good	4.3
	VERY HIGH	**10**	**0**	MDIV	Bad condition	4
2	REMOTE	**3**	**50**	TWO LANES	good condition	2.5
	RURAL	**5**	**150**	MUND	Bad condition	2.8
	SUBURBAN	**7**	**20**	MDIV	Many intersect.	3.8
	URBAN	**9**	**10**	MDIV	Very good	4.3
	VERY HIGH	**10**	**10**	MDIV	Bad condition	4
3	REMOTE	**3**	**250**	TWO LANES	good condition	2.5
	RURAL	**5**	**100**	MUND	Bad condition	2.8
	SUBURBAN	**7**	**10**	MDIV	Many intersect.	3.8
	URBAN	**9**	**0**	MDIV	Very good	4.3
	VERY HIGH	**10**	**0**	MDIV	Bad condition	4

Route 3 is longer than the other two routes but it does not intercept highly populated areas. Four different cases have been used with the three routes. The conditions for each case are presented in Table 6:

Table 6: Description of the four cases used as example

		CASE 1	**CASE 2**	**CASE 3**	**CASE 4**
	CHEMICAL	Chlorine	Chlorine	Chlorine	Chlorine
	ERPG-2 (ppm)	3	3	3	3
	NFPA FIRE	0	0	0	0
	NFPA EXP	0	0	0	0
	Tb (F)	-29	-29	-29	-29
TRUCK	Type	single trailer	single trailer	double trailer	single trailer
	VOL (gal)	4,000	4,000	4,000	4,000
	T (F)	80	80	80	32
	P rating (psi)	400	400	400	400
STORAGE TANK	VOL (gal/yr)	20,000	20,000	20,000	20,000
	tank VOL (gal)	5,000	8,000	8,000	8,000

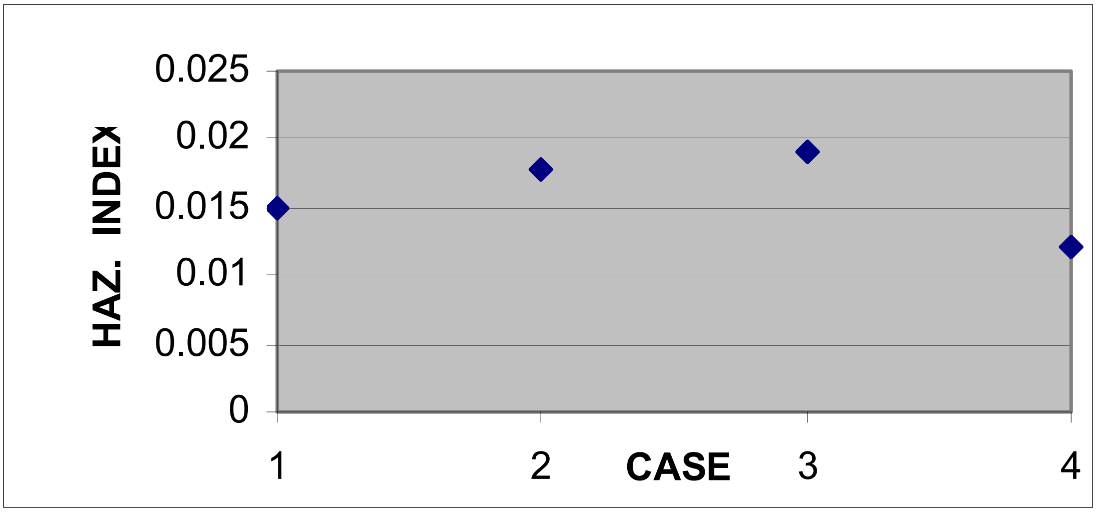
The results reported in Table 7 are for the first route and the first three cases. It is possible to observe how the accident rate and release probability change depending on the environment and the type of truck. Also, it is possible to observe how the total hazard indices change depending on the route and the conditions of each combination of case and route.

Table 7: Results for Cases 1, 2, 3 for Route 1

CASE		HAZ INDEX	Rel. Prob.	Acc/mi	Rel. prob.	Rel. rate
1	REMOTE	0.003204	0.000641	5.79E-06	0.0626	3.62E-05
	RURAL	0.003031	0.000606	8.94E-06	0.05747	2.57E-05
	SUBURBAN	0.001582	0.000316	9.94E-06	0.0527	1.05E-05
	URBAN	0.001603	0.000321	8.08E-06	0.05	8.09E-06
	VERY HIGH	0	0	1.06E-05	0.05	0
		0.00942				
2	REMOTE	0.001602	0.00032	5.70E-06	0.0626	1.81E-05
	RURAL	0.009093	0.001819	8.94E-06	0.05747	7.71E-05
	SUBURBAN	0.001582	0.000316	9.94E-06	0.0527	1.05E-05
	URBAN	0.0008017	0.00016	8.08E-06	0.005	4.04E-06
	VERY HIGH	0.001104	0.000221	1.06E-05	0.05	5.29E-06
		0.0141				
3	REMOTE	0.00801	0.001602	5.78E-06	0.0626	9.06E-05
	RURAL	0.006062	0.001212	9.94E-06	0.05747	5.14E-05
	SUBURBAN	0.000791	0.000158	9.94E-06	0.0527	5.24E-06
	URBAN	0	0	8.08E-06	0.005	0.00E+00
	VERY HIGH	0	0	1.06E-05	0.05	0.00E+00
		0.0148				

In Figure 5 the total hazard indices are plotted for Cases 1, 2, 3 and 4 on Route 3. It is possible to observe how Case 3 (double pressurized trailer) seems to present the higher potential hazard while Case 4, single refrigerated trailer, offers the safest option among the four studied.

Figure 5: Total hazard index for Cases 1, 2, 3, and 4 for Route 3.



CONCLUSIONS AND FUTURE WORK

The fuzzy logic methodology described in this paper represents the first step in the development of a transportation index that can be included in the overall inherent safety evaluation of a chemical plant. This methodology must be expanded to other transportation modes, such as railroad, pipelines, and barges, and each one of these modes represents a different problem that must be analyzed by taking into account the data available and the knowledge obtained from it. Fuzzy logic provides a flexible approach to model transportation problems because of its ability to work with uncertain data and include subjective evaluations.

The results obtained from the sets of experiments is encouraging, but more tests must be performed to assess the efficiency of the fuzzy inference systems used, including the design of the membership functions. The total calculated hazard must be transformed into an index on a specific scale. However this step is not developed here because more evaluations and a general consensus on the degrees of hazards are required.

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