

JRC2014-3851

FLAMMABLE LIQUID FIRE CONSEQUENCE MODELING

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ABSTRACT

The recent expansion in the production of shale petroleum crude oil, combined with the lack of new pipeline construction, has placed the railroads at the center stage for safe and efficient transport of very large volumes of this commodity. Petroleum crude oil poses fire risk in the event of train accidents. The consequence modeling based on the US DOT Emergency Response Guidebook (ERG) or ALOHA (Areal Locations of Hazardous Atmospheres), a popular atmospheric dispersion model used for evaluating releases of hazardous chemical vapors, may be overly simplistic and limited to estimate the risk of flammable liquid releases. This paper aims to address this gap and develop a simple model to estimate flammable liquid release consequences, focusing on petroleum crude oil. A flow model using the spatial geographic information system (GIS) and the digital elevation model (DEM) is developed. The methodology was illustrated with a case study comparing the results from the model to the area affected from the Lac-Mégantic accident. Although the model does not consider advanced flow types or fire propagation, the results accurately describe the consequences of the accident, demonstrating the potential capability of this methodology to estimate the consequences of a crude oil release.

INTRODUCTION

Arguably the worst railroad accident in more than a century in North America took place on July 6th, 2013 in Lac-Mégantic, Quebec, Canada. The derailment of 63 out of 72 tank cars transporting petroleum crude oil, and consequent releases of several of these cars, devastated the downtown area destroying more than 30 buildings, caused 47 fatalities (5 are still officially missing), and triggered the evacuation of about 2,000 people [1]. Despite this tragic accident, North American railroads are considered one of the safest modes of transportation for hazardous materials, “with 99.9977 percent of all shipments reaching their destination without a release caused by an accident” [2].

Given their reliability, railroads will continue transporting large volumes of crude oil and other hazardous materials. However, events like the Lac-Mégantic accident highlight the need to further improvement in railroad hazmat transportation safety, and particularly of the consequence assessment for crude oil transported by rail. The lack of a specific consequence model for flammable liquid hazmat releases is addressed in this paper. A flow model using the spatial geographic information system (GIS) and the digital elevation model (DEM) is developed. The model can be used to predict the area of potential fire exposure and prioritize emergency responses. A case study simulating the accident in Lac-Mégantic is also

performed and compared to the real consequences of the accident to illustrate the potential capabilities of this model.

Risk assessment for railroad hazmat transportation can be defined as the product of the probability of a derailment and the consequence of the derailment [3, 4]. The consequences of a hazmat release may be measured in terms of population affected (injury, fatality and/or evacuation), property damage, and/or environmental impacts, and they depend directly on the type of chemical, the quantity of release, and the specific characteristics of the release location (e.g. weather condition, terrain surface). Among others, the scope of this paper is to describe the possible consequences of a crude oil release and highlight the reasons why other consequence models are not appropriate for modeling the viscous chemical.

Crude oil is a liquid hazardous material that behaves mainly as a nontoxic flammable chemical [5]. This means that in case of an accidental spill, the product will spread over the terrain and, as any other liquid, will flow downslope. It is probable that the product will ignite, immediately or sometime after the accident, when it reaches an ignition source. In addition, the gases emanated from the liquid can also be ignited and produce explosions or flash fires. This will depend directly on the material's volatility and the concentration of the gases in the environment. Given the low evaporation rate of crude oil, in general, the vapor consequence may not be the major concern. It is probably more appropriate to model crude oil releases as a liquid, taking into account the terrain where the spill takes place and its propagation downslope to determine the areas affected.

LITERATURE REVIEW

Previous research calculated the affected area of a hazmat release incident by using a circular area centered at the release point, assuming a uniform distribution of the chemical in all directions [6]. Although this assumption may be adequate in other cases, it is not suitable for crude oil propagation modeling. As has been explained before, the flow propagation depends directly on the terrain surface. Therefore, assuming a uniform chemical distribution around the point of release would imply that the terrain surface is also uniform. This approach is too simplistic given the general heterogeneity of the ground surface. For example, two points, one uphill and the other one downhill, located at the same distance from a spill source would not be affected in the same way by the release. The point uphill would have a low likelihood to be affected while the point downhill would have a high likelihood to be affected. The area affected will have an irregular shape depending on the specific characteristics of the land surface in the region.

Besides the shape, another important aspect to define the area affected is the size of the release area. In general, the maximum distance where the hazmat concentration is harmful to the general public is used to outline the area affected.

Different models are available to estimate this distance, including the Emergency Response Guidebook (ERG) developed by the U.S. Department of Transportation [7], which is widely used by planners and emergency responders. This guidebook provides an initial isolation distance for each specific hazardous materials and it can be used to calculate the exposure zone for a release. The ERG value is a fixed distance that does not consider any specific condition such as the terrain slope.

Another model, called the Gaussian Plume Model (GPM), is facilitated by advanced computing capabilities and can be used to calculate the chemical concentration after a release [6]. The GPM is widely used because it combines a simple and flexible mathematical expression and realistic results validated by diverse laboratory and field experiments. However, not all chemical releases can be modeled using GPM. This model specializes in gases, therefore not suitable to model liquid hazmat. Moreover, most software that uses GPM, (e.g. ALOHA) assume flat terrain and only one source of release.

Since traditional approaches for modeling hazmat releases are limited to model a crude oil release, it is necessary to propose a new approach capable of modeling this scenario more accurately. This new approach must consider the irregular terrain and the possibility of multiple sources of release to accurately estimate the area affected by the spill. The technique proposed in this paper is the geospatial flow modeling using a digital elevation model (DEM). A similar technique has been successfully applied previously in pipeline release consequence modeling [9, 10]. This research adapts the same technique and extends the methodology by taking into account the specific characteristics of the railroad industry.

METHODOLOGY

Geospatial techniques refer to computer-based methods for gathering, managing, analyzing, and displaying spatial data [11]. In our study, geospatial techniques are applied to flow modeling using diverse spatial information (e.g. DEM). A DEM is a type of spatial data called raster data, with information about the elevation of an area. It is fundamentally a matrix of pixels where each pixel has its own coordinates and a value of elevation (Figure 1).

95	90	87	81	87
99	87	75	67	65
75	65	58	50	57
55	50	40	45	35
60	45	32	22	27

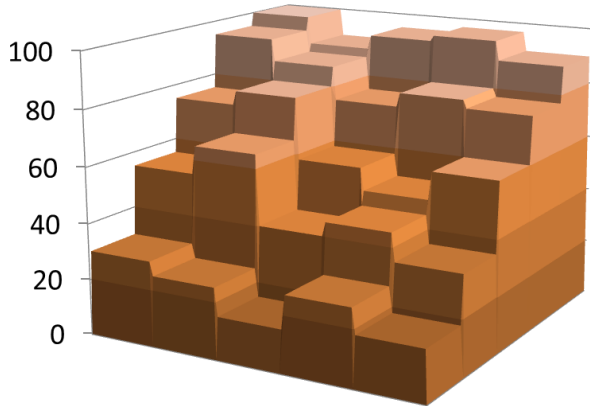


Figure 1 Matrix of pixels and 3D representation of a Digital Elevation Model (DEM)

The resolution of the DEM (i.e. the pixel size) may considerably affect the quality of the final result. Therefore it is important to obtain the best data available for the area studied. With this information, the analysis to determine the direction of the flow at a release area can be performed. ESRI's ArcMap software was chosen to perform this analysis, but any similar GIS software can be used for the same purpose.

The quality of the results from the analysis is affected by the quality of the raw data and the assumptions adopted for the flow modeling. In this paper, the basic assumption is based on the intuition that overland flow moves downhill by the steepest path. This means that any liquid on a pixel will move to the pixel with the lowest elevation in the neighborhood of the original pixel. At maximum, each pixel may have eight neighbors, then a drop has eight possible paths to continue its trip downhill. This assumption does not consider the advanced flow modeling with different types of flow (e.g. flat, pool) [12]. Future research may address the types of flow, the flow speed and the quantity of release.

Once the basic assumptions are established and the data is obtained from reliable sources, the analysis would start by setting the points of release. There are two different perspectives for establishing the points of release. The first is from the planner's perspective, where the analysis is used to estimate the consequences of a hypothetical event. The second is from the emergency responder's perspective, in which the

analysis is used to help the emergency teams identify and prioritize the affected areas.

For the planners, the railroad line must be discretized into all possible points of release that would result in a potentially different flow path. Given that all the points within a DEM pixel will result in the same flow path, the rail line must be discretized into as many points as different pixels the overlaid line (Figure 2).

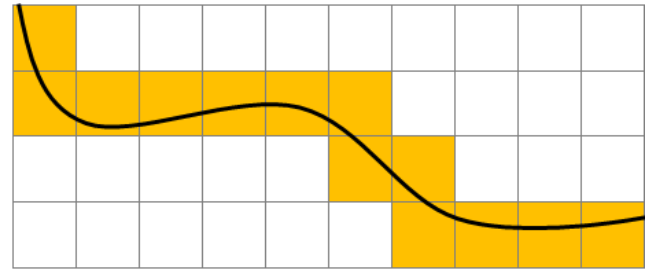


Figure 2 Discretized line based on the raster pixel size

After the discretization is performed, the planner will need to analyze all potential points of release, and the final result will be the envelope of all those potential flow paths. It is noteworthy that as the resolution of the DEM increases, the number of points will increase, thus increasing the computational time. Addressing the tradeoff between data resolution and computation time can be challenging.

Alternatively, from the emergency responder's perspective, the point of release may have already been established since the accident has already happened. They should also consider that an accident can be represented by one or multiple points of release depending on the size of the accident. Unlike the planner's analysis, this analysis could be performed in a short time, which is required in an emergency situation.

After setting the points of release, the following step is to analyze the DEM and extract the useful information from it. There are several different tools already implemented in ArcMap that can be used to derive the information from a DEM. Two of those tools are chosen to perform the analysis: Flow Direction and Flow Accumulation. The first tool provides a new raster file, where the value of each pixel represents the direction of the steepest drop from this cell to the next one. As each cell has a maximum of eight neighbors, there are eight possible values for the eight possible directions (Figure 3).

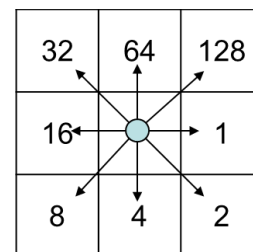


Figure 3 Possible values from the *Flow Direction* tool

The second tool, Flow Accumulation, determines how many cells flow into every subsequent cell. This tool is used to identify the cells where the released commodity is accumulated in a determined area [13].

Finally, the analysis concludes by selecting the steepest path for each point of release. Although there is no direct tool to perform this selection automatically, this operation can be easily programmed within ArcMap. Looking at the value on each pixel in the output raster from the Flow Direction tool, the direction of the steepest path can be obtained and used for selecting the next pixel. After the steepest path has been completed, the areas affected can be identified in a map and the consequences can be estimated.

The summary of the methodology is shown in Figure 4.

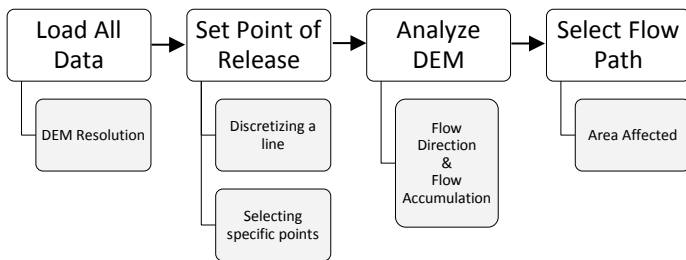


Figure 4 Methodology flow chart

CASE STUDY

To illustrate this methodology and demonstrate its applicability to a real consequence estimation analysis, a case study of the Lac-Mégantic accident is performed. The consequences of the accident are estimated using the geospatial techniques discussed in the previous section. The results of the analysis are then compared to aerial pictures after the accident.

The required spatial data was downloaded from the Natural Resources Canada website [14] for the specific area of Lac-Mégantic, Quebec. The data required for this study includes two main groups of data: vector and raster data. The vector data consists of the railroads, the streets, and the lake shoreline. The raster data includes the DEM (Digital Elevation Model) and the satellite image of the area. The DEM has a resolution of roughly 20 meters.

Once the data had been loaded within ArcMap (Figure 5), the next step was to set the points of release. In this example, the points of release were estimated based on the approximate location of the tank-car pile from the pictures taken after the accident. Given that the pile occupies an extensive area, four points of release were set and analyzed.

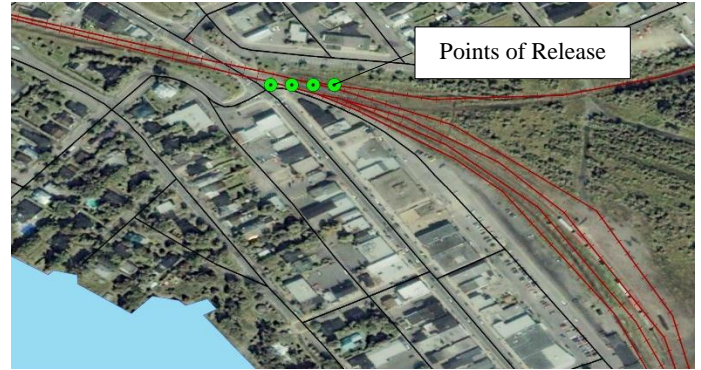


Figure 5 Situation Map

After the release points had been set, the following step in the process was to analyze the DEM and extract the useful information from it. In this example, the two output rasters were combined into one layer of points (Figure 6). Each pixel is represented by one arrow which indicates the flow direction and the relative accumulation in the pixel – the heavier the color the higher the accumulation.

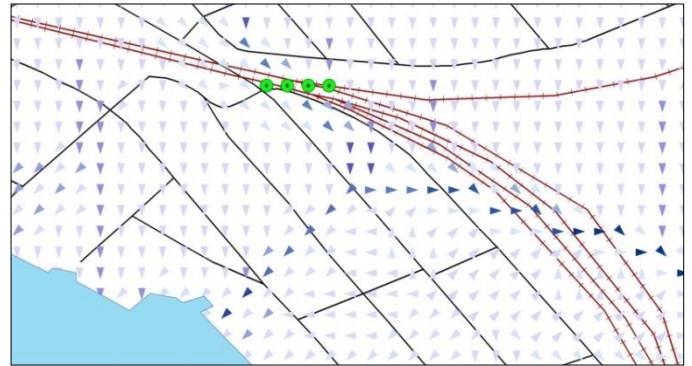


Figure 6 Flow direction and flow accumulation results

The arrows point to the steepest path so, as the flow is assumed to be governed by the steepest path, the final flow path is indicated by the successive arrows. This operation can be done either automatically, through a programming code, or manually by selecting the consecutive arrows. The final paths and area affected are shown in Figure 7 overlying the satellite image to facilitate the posterior comparison with the real picture of the accident.

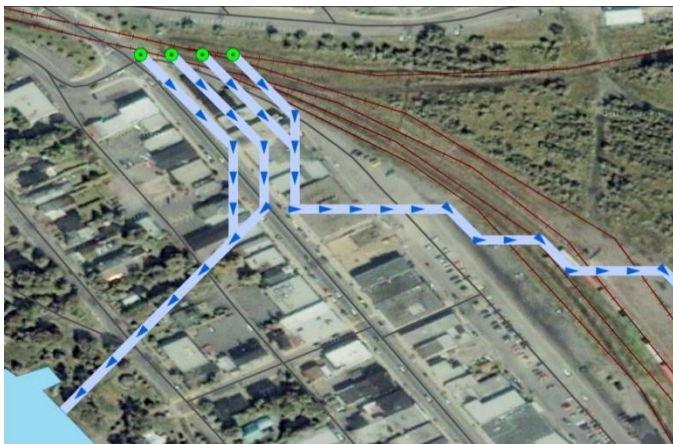


Figure 7 Flow paths estimated from the analysis

The model results on Figure 7 can be compared to the accident picture on Figure 8. The model accurately predicts which area of the city would be more damaged, and the point of entry of the hazmat into the lake. Although in the actual photo, it seems like the area affected is wider, it is clear how this model is able to predict that two main different flow paths will be formed after the accident: a path through the city and another path toward the rail tracks. The wider area affected compared to the model could be the consequence of the violent fire ignited immediately after the accident. The fire could have propagated to adjacent buildings and affected an area that would have not been affected in a non-fire event. It is important to mention that this methodology does not evaluate the possible propagation of a fire after an accident occurs. However, a buffer distance around the flow path could be used as an estimation of a fire event, and therefore it could be taken into account for risk analysis purposes. More case studies are needed to fully validate this model.



Figure 8 Real picture to compare between the model results and the reality after the accident

CONCLUSIONS

This paper presents a methodology to estimate the area affected by a crude oil release from a potential railroad accident by using geospatial techniques and the DEM. This methodology considers the specific conditions of the terrain near release areas providing more realistic results than other existing methodologies. The methodology was illustrated with a case study comparing the results from the model to the area affected from the Lac-Mégantic accident. Although the model does not consider advanced flow types or fire propagation, the results accurately described the consequences of a real accident, demonstrating the potential capability of this methodology to estimate the consequences of a crude oil release. Moreover, given its relatively easy and quick implementation using a computer software, it would be a powerful resource for emergency responders and planners to predict and prioritize release areas in a railroad accident.

ACKNOWLEDGMENTS

This research was funded by the National University Rail (NURail) Center, a U.S. DOT University Transportation Center. The authors are grateful to the useful comments from the anonymous reviewers.

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