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Developing a chaotic pattern of dynamic Hazmat routing problem ☆

Abbas Mahmoudabadi [a,*], Seyed Mohammad Seyedhosseini [b]

[a] Department of Industrial Engineering, Payam-e-Noor University, Tehran, Iran
[b] Department of Industrial Engineering, Iran University of Science & Technology, Tehran, Iran

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ABSTRACT

The present paper proposes an iterative procedure based on chaos theory on dynamic risk definition to determine the best route for transporting hazardous materials (Hazmat). In the case of possible natural disasters, the safety of roads may be seriously affected. So the main objective of this paper is to simultaneously improve the travel time and risk to satisfy the local and national authorities in the transportation network. Based on the proposed procedure, four important risk components including accident information, population, environment, and infrastructure aspects have been presented under linguistic variables. Furthermore, the extent analysis method was utilized to convert them to crisp values. To apply the proposed procedure, a road network that consists of fifty nine nodes and eighty two-way edges with a pre-specified affected area has been considered. The results indicate that applying the dynamic risk is more appropriate than having a constant risk. The application of the proposed model indicates that, while chaotic variables depend on the initial conditions, the most frequent path will remain independent. The points that would help authorities to come to the better decision when they are dealing with Hazmat transportation route selection.

1. Introduction

As hazardous material (Hazmat for short) transportation covers a significant part of economic activities in most industrialized countries, management of Hazmat is a multimodal issue involving environmental, engineering, economical, societal as well as political concerns [1,2]. Determining the route for Hazmat, known as the Hazmat routing problem, is usually a double-sided problem, where local authorities move towards minimizing public risk, while the carriers are concerned about minimizing transport costs [3].

Many different attributes as well as operation research methods are currently utilized to solve the Hazmat routing problem. In terms of attributes, social problems alongside out-of-pocket costs are the main considerations in developing mathematical models for solving risk-oriented optimization problems [4]. While the risk of spreading Hazmat in accidents and transport cost are considered as the main attributes for developing a mathematical model to determine the optimal assignment of truck flow within transportation, minimizing the weighted combination of objectives is also observed in the literature [5]. Dependency of travel time and risk associated to road network upon road traffic measures [6], road geometric designs [7,4], weather condition [8] and safety regulations which are imposed on drivers and transport companies [9] are also known as attributes in Hazmat routing problems. Population [5,10,11], environment [8,11–13] and accident [1,5,7,9,14] are the main apprehensions to define risk associated with Hazmat incident impacts. Specified regional networks which have been assigned by local authorities for Hazmat transportation, particularly for better enforcement and improving road safety, lead researchers to solve Hazmat routing problem [15–18] under network constraints. In addition, the nature of hazardous materials [4,19] together with public security [17] have also been studied as important attributes in this area. Management issues such as road network and vehicle capacity planning [10,20], Hazmat delivery time [1,7], and eventually emergency response have been considered in the above problem [5,12,14,19].

In terms of operation research methods, a two-stage approach was utilized to solve the problem of daily routes as well as departure intervals for Hazmat transportation trucks [7]. Within the first stage, a set of minimum and equitable risk routes are defined for each Hazmat transportation in order to spread the risk equitably over the population, while in the second stage, one among the aforementioned routes and a departure time not less than the preferred one, are assigned to each Hazmat transportation route in order to assure that at any given time, every two vehicles must be sufficiently far apart to minimize the sum of the Hazmat shipment delays [7]. K shortest path algorithm was developed for stochastic and dynamic networks and focused on identifying the exact solution to lead to computational inexplicit in large networks [15]. Defining bi-level objective function is another technique to solve the Hazmat routing problem [9,11,16]. To give an estimate, Serafini [11] developed a bi-level objective function model for the specific problem and extended a dynamic programming

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* Corresponding author. Tel.: +98 912 159 7537; fax: +98 21 88890826.
E-mail address: mahmoudabadi@phd.pnu.ac.ir (A. Mahmoudabadi).

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model to use for larger classes of network. As a more common technique, developing a mathematical model based on different priorities of attributes is also utilized to define objective function [1,5,21], in which each attribute is weighted by own weight of importance for modeling.

Some researchers have made research works in to clear routing as well as scheduling problem of Hazmat transportation in this area. Travel time and consequence measures are considered inherently unreliable and stochastic because of their dependencies upon characteristics like visibility, traffic volumes and activity patterns [6], while in the terms of uncertainty, weather condition was a main parameter in Hazmat routing problem [8]. Population risk and travel time are defined using probability distribution function to develop a multi-objective function for routing Hazmat transportation [5] due to the variation of the traffic condition over the network. Solving routing problem together with schematic points, made by Androuspolous et al. [9] to develop a mathematical model, considers Hazmat transport problem regarding dynamic risk to daily time while safety regulation made drivers to stop and rest in pre-specified locations.

Although transport risk of hazardous material is usually quantified with a path evaluation function [22], uncertainty is still considered in Hazmat routing problem. For more detail, in a typical research work presented by Dadkar et al. [23], the probability of assassination attacks has been verified in due model using stochastic variables. In another research work, done by Reilly et al. [18], while having the case studied through GAME theory, improvement was achieved by defining the probability of assassination attack. They defined transport companies, terrorist bodies and local authorities as game players to develop their model. The other types of defining risk including stochastic, uncertainty and linguistic are also observed in the area of Hazmat routing problem in academic literature. Qiao et al. developed a fuzzy model to estimate frequency of Hazmat transport accidents using a qualitative approach where driver, road construction and truck characteristics are presented as membership function based on experts' experiences [24].

According to the above, the use of probability function would seem as an appropriate approach to define risk. However, Hazmat road accidents incorporating their impacts might be more complicated compared to chaotic patterns which seem to be in regard of defining their characteristics for Hazmat routing problem.

Despite hazardous material transport risks being usually quantified by distribution functions [16], lack of reliable data, particularly in developing countries, will hamper to achieve the best routes in Hazmat transport planning. In the present case, an appropriate way of data collection is suggested for gathering experts' comments on using linguistic variables and converting them to the crisp values to be used in the process of developing and running mathematical models.

Although road safety in hazardous material transportation is definitely found to be much more important compared to other aspects, population must be protected from natural disasters as soon as possible [25], so trip time cannot be underestimated as a main criterion for vital substances transportation. Because flammable liquids are known as hazardous materials according to the hazardous material classification [26], fuel could be named as a main substance to be viewed for emergency situations in which time is a major concern for local authorities.

The main concept behind the present paper is to propose a methodology to help decision makers to achieve the best routes for Hazmat transportation under the emergency situations as soon as possible, while the other aspects of critical management such as people evacuation or first aid services have not been considered. In other words, the main concept behind the proposed methodology is to find the route for Hazmat transportation in which national and/or local authorities would make correct decisions in emergency situations while people who are settled in the affected area reach the requirements as soon as possible but other residents are not involved by Hazmat transport impacts. An other problem is that there is no exact data on road accidents; travel time might be a more important concern for carrying vital substances of Hazmat in emergency situations and behavior in road accidents seems to follow dynamic patterns due to the complexity of road accidents. The present paper is articulated in three main parts. The first part attempts to check the dynamic behavior of road accidents based on chaos theory. In order to cover a wide-range of variation, risks are defined by the chaotic pattern of one-dimensional logistic map equation as well as having analyzed during an annual period. The novelty in this paper is focused on using the chaotic property of traffic incidents such as traffic flow theory [27] in the process of solving Hazmat routing and scheduling problem, while risk in Hazmat transportation corresponds to four components including accident, population, environment and infrastructure due to accident impacts of Hazmat. The second part consists of a main subject to gather experts' considerations of risk according to the above components of risk and converts them to crisp values. The last one is to propose an iterative methodology to generate dynamic risk of the above risk components followed by a mathematical model, validation process and sensitivity analysis.

Consequently, the article is arranged in seven sections including introduction, brief description of chaos theory and presence of chaos as well as extent analysis method. They are followed by defining procedure and developing mathematical model, case study and experimental data embracing linguistic variables and converting them to crisp values, running proposed procedure incorporating problem definition, comparing results and sensitively analysis and summary, conclusions and recommendations to future studies, respectively.

2. Chaos theory and presence of chaos

Edvard Lorenz introduced the concept of chaos theory in 1963. He found the chaotic attractions in complex systems of weather forecasting when he entered different values as starting points in a computer program [28]. Chaos has been studied within the engineering scientific and mathematical communities and found to be useful in many disciplines such as high-performance circuits and devices, collapse prevention of power systems and also information processing [29]. Some sudden and dramatic changes in nonlinear systems may give rise to the complex behavior called chaos [27]. A nonlinear system is said to be chaotic if it exhibits sensitive dependence on initial conditions. It may happen that small differences in the initial conditions produce very great ones in the final outputs [30]. Chaos theory is commonly applied for short-term prediction because of the existing property of "sensitive dependence upon initial condition", which would hamper the success of long-term prediction, in respect. It has been widely applied on various fields of science particularly in the area of traffic flow theory [27].

Since chaos theory is used to analyze complex systems and transportation systems are complex entities, it may be found useful for transportation applications. In transportation systems, legal and social constraints may bind behavior, allowing a researcher to more accurately predict human actions and system evolution [31,32].

Determining the presence of chaotic behavior is a very important step. The Lyapunov characteristic exponent, λ, is the clearest measure to prove the existence and to quantify chaos in a dynamical system or time series [33]. Calculating the largest Lyapunov exponent is a more common technique to determine the presence of chaos, which measures the divergence of nearby trajectories [31]. As the system evolves, the sum of a series of convergence in each dimension will converge or diverge. Lyapunov exponents measure the rate of convergences and divergences in each dimension. If the largest Lyapunov exponent is positive, it indicates that the system under investigation is sensitive to initial condition and is chaotic. Eq. (1) is used to determine the largest Lyapunov exponent, λ_{max}, where $S(t)$ is the system situation in period (t) and $S'(t)$ is its nearest neighbor. In this