Accident Analysis and Prevention 43 (2011) 1267–1278

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

A stochastic catastrophe model using two-fluid model parameters to investigate traffic safety on urban arterials

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ARTICLE INFO

Article history:
Received 8 July 2010
Received in revised form
22 December 2010
Accepted 13 January 2011

Keywords:
Catastrophe model
Urban arterials
Two-fluid model
Pro-active safety

ABSTRACT

During the last few decades, the two-fluid model and its two parameters have been widely used in transportation engineering to represent the quality of operational traffic service on urban arterials. Catastrophe models have also often been used to describe traffic flow on freeway sections. This paper demonstrates the possibility of developing a pro-active network screening tool that estimates the crash rate using a stochastic cusp catastrophe model with the two-fluid model's parameters as inputs. The paper investigates the analogy in logic behind the two-fluid model and the catastrophe model using straightforward graphical illustrations. The paper then demonstrates the application of two-fluid model parameters to a stochastic catastrophe model designed to estimate the level of safety on urban arterials. Current road safety management, including network safety screening, is post-active rather than pro-active in the sense that an existing hotspot must be identified before a safety improvement program can be implemented. This paper suggests that a stochastic catastrophe model can help us to become more pro-active by helping us to identify urban arterials that currently show an acceptable level of safety, but which are vulnerable to turning into crash hotspots. We would then be able to implement remedial actions before hotspots develop.

1. Introduction

Lord and Mannering (2010) provided a chronological and comprehensive review of statistical road safety models published in the literature during the past few decades. They focused on reviewing the methodological approaches used in the various statistical models to estimate the crash frequency (or crash rate) of target locations. In general, the various statistical models have been introduced to resolve the different technical issues embedded in the estimation of crash frequency (or crash rate). Poisson models and Poisson-gamma models are good examples. Poisson models were introduced to deal with (crash) frequency data, i.e. non-negative integers, for which traditional linear regression techniques are not entirely appropriate (Jovanis and Chang, 1986; Miaou, 1994). Poisson-gamma models were later introduced primarily to resolve the over-dispersion issue in crash frequency data (Hauer et al., 1988; Maher and Summersgill, 1996; Lord and Park, 2008), Poisson-gamma models have now become the standard statistical model used to estimate crash frequency on road networks in North America (AASHTO, 2010). In addition, advanced statistical models, such as the Conway–Maxwell–Poisson model (Lord et al., 2008) and the gamma model (Oh et al., 2006), have been proposed in order to handle under-dispersed data as well as over-dispersed data in the statistical modeling process.

Even more recently, two non-conventional statistical models, the finite mixture model (Park and Dominique, 2009) and the Markov Switching count data model (Malyshkina et al., 2009; Malyshkina and Mannering, 2010), have been developed to estimate crash frequency. (The Markov Switching count model can be viewed as an extension of the finite mixture model.) These models use a mixture of multiple distributions to take the potential heterogeneity and over-dispersion issues found in crash data into account. The models provide superior fitting results. Interestingly, the Markov Switching count model, in particular, assumes (unobserved) distinct safety states (e.g., a safe state and a less safe state) for a target roadway. The model allows for change (or transition) in the safety states of the target roadway over a period of time by applying distinct distributions to represent different safety states. The concept of change (or transition) in the safety state over time has very important implications for the current study (and is discussed in-depth in the section on "Background Theories").

In addition to the methodological issues involved in statistical models developed to estimate the level of safety, the issue of

☆ This paper was presented at the 90th Annual Meeting of the Transportation Research Board.

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doi:10.1016/j.aap.2011.01.009

(inappropriate) input parameters is also important. In the case of urban arterials, in particular, a typical approach is simply to use very high level (aggregate level) traffic flow parameters such as average daily traffic (ADT), and then to relate the traffic flow parameters to the crash frequency or crash rate using the various statistical methods outlined above. It can, however, be extremely difficult to develop and select appropriate traffic flow parameters that rely solely on the so-called “best-fit statistical model,” and extremely difficult to give much consideration to the underlying mechanism, i.e., the logic in the relationship between the safety measures (such as crash frequency or crash rate) and the traffic flow parameters. These difficulties may arise because, despite the large number of tests conducted, we lack supporting theories to underpin the input parameter development and selection process.

This study can be regarded as an extension of Malyshkina and Mannering’s (2010) work in the sense that, like Malyshkina and Mannering, we also investigate the potential change (or transition) in the level of safety over a period of time. In this study, we consider urban arterials using a different modeling approach (i.e., a stochastic catastrophe model) to show the potential change in the level of safety, and we also look into the potential benefits of applying two input parameters obtained from a macroscopic traffic flow theory (i.e., from two fluid theory) as surrogate indicators for representing the level of safety on an urban arterial.

The study was also undertaken partly to investigate the possibility of developing a single measure that could be used to describe both operational traffic efficiency and traffic safety, and partly in response to the problem that the regression-type models commonly used in transportation engineering to identify crash hotspots are largely limited to statistical curve fitting models, and therefore lack a theoretical underpinning that can explain how the models behave and operate.

The study’s objectives can be summarized under four headings:

1. To demonstrate the similarities in logic behind two-fluid theory and catastrophe theory using descriptive and graphical approaches.
2. To develop stochastic catastrophe models, and demonstrate how to apply macroscopic traffic flow parameters in order to represent the level of safety on an urban arterial.
3. To illustrate the underlying mechanism of transition in the level of road safety that may be viewed as a catastrophe phenomenon by the change in input parameters (i.e., change in macroscopic traffic flow parameters).
4. To explore the possible applicability of the two theories (i.e., two fluid and catastrophe theories) in road safety research, and whether they could be improved and built on in future research with more comprehensive data availability.

The paper starts by describing two theories (two-fluid theory and catastrophe theory) that may enable us to assess the transition in the level of safety of an urban arterial over a time period. Although this study approach will be rather theoretical in nature, future study may investigate the benefit from applying these theories to real safety projects and may help transportation engineers can implement remedial actions pro-actively before a hotspot develops.

2. Background theories

2.1. Two-fluid theory

Herman and Prigogine’s two-fluid theory (Herman and Prigogine, 1979) is a popular macroscopic traffic flow theory often used to evaluate operational traffic performance on a given urban arterial (Williams, 2001; Jones and Farhat, 2004). Many earlier studies also used the two fluid theory, for example, to compare changes in the operational performance of an urban arterial over time in response to traffic signal changes (Vo et al., 2007), to investigate the impact of selected geometric features (e.g., average block length, average number of lanes per street, or intersection density) on the operational traffic quality of downtown streets (Ardekani et al., 1992), or even to estimate the magnitude of fuel consumption in different metropolitan areas (Chang and Herman, 1978; Herman and Ardekani, 1985). Recently, an attempt was made to show the statistical association between two-fluid theory parameters and safety on urban arterials (Dixit et al., 2009a).

The two-fluid theory was originated by analogy to an exotic quantum phenomenon known as the Bose–Einstein condensate (BEC). The BEC phenomenon was first observed in the atoms of a gas, and describes the dramatic transition in the energy state of atoms at extremely low temperatures (very near absolute zero, −273.15 °C). At ordinary temperatures, the atoms of a gas are scattered throughout the system holding the atoms, and some of the atoms are in a high energy state with a high speed, and others are in a low energy state with a low speed. Bose, and later Einstein, showed mathematically that if atoms with a high energy state in a system can be cooled sufficiently, the energy state of a large fraction of the atoms will change to the single lowest possible energy state (i.e., ground state with zero speed) in the system (Cornell and Wieman, 1998). In the application of the two-fluid theory to traffic, a traffic flow stream on an urban arterial is divided into two distinct traffic flow states: mobilized and immobilized. The immobilized traffic flow state might consist of vehicles stopped due to roadway congestion or traffic controls. This state is considered analogous to the atoms in the ground state in a gas system, and is expected to show zero speed. The essential principle of the two-fluid theory is the assumption of multiple traffic states and the implied assumption of transition between the traffic states.

The fundamental concept underlying the BEC phenomenon can further be illustrated in the gas–liquid condensate diagram provided by Jost and Nagel (2003). Jost and Nagel stated the following (see Fig. 1(a)):

1. *In the gas state, at low densities, particles are spread out throughout the system... and the probability of having two particles close to each other is very small.*
2. *In the liquid state, at high densities... the particles are so close to each other, it is difficult to compress the fluid any further.*
3. *In between, there is the so-called coexistence state, in which gas and liquid coexist.*

Fig. 1(b) shows that only one state exists in a gas–liquid system beyond a certain temperature ($T > T^*$; where, T^* = critical temperature), and that no transition between states occurs. On the other hand, multiple states (gas, liquid, and coexistence states) exist under the critical temperature. The transition between states is determined by the magnitude of density. In Fig. 1(b), the inverse-*U* curve (the red line) represents the boundary of different gas–liquid states. The liquid state in Fig. 1(a) and (b) is analogous to the ground energy state of atoms at extremely low temperature in the BEC phenomenon.

Two-fluid theory considers the traffic state on urban arterials as multiple states: mobilized and immobilized. The immobilized traffic state can be compared to the liquid state of particles in a gas–liquid condensate. The mobilized traffic state can be compared to the combined gas and coexistence states.