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An improved cellular automaton with axis information for microscopic traffic simulation

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ABSTRACT

Cellular Automaton (CA), an efficient dynamic modeling method that is widely used in traffic engineering, is newly introduced for traffic load modeling. This modeling method significantly addresses the modest traffic loads for long-span bridges. It does, however, require improvement to calculate precise load effects. This paper proposed an improved cellular automaton with axis information, defined as the Multi-axle Single-cell Cellular Automaton (MSCA), for the precise micro-simulation of random traffic loads on bridges. Four main ingredients of lattice, cells' states, neighborhoods and transition rules are redefined in MSCA to generate microscopic vehicle sequences with detailed vehicle axle positions, user-defined cell sizes and time steps. The simulation methodology of MSCA is then proposed. Finally, MSCA is carefully calibrated and validated using site-specific WIM data. The results indicate: (1) the relative errors (REs) for the traffic parameters, such as volumes, speeds, weights, and headways, from MSCA are basically no more than ±10% of those of WIM data; (2) the load effects of three typical influence lines (ILs) with varied lengths of 50, 200 and 1000 m are also confidently comparable, both of which validate the rationality and precision of MSCA. Furthermore, the accurate vehicle parameters and gaps generated from MSCA can be applied not only for precise traffic loading on infrastructures but also for the accurate estimation of vehicle dynamics and safety. Hence, wide application of MSCA can potentially be expected.

1. Introduction

Traffic simulation is a fundamental method for traffic engineering and transportation infrastructures. In traffic engineering, the objective of traffic simulation is to generate realistic traffic flows reflecting inherent vehicle behaviors and observed traffic phenomena. For transportation infrastructures such as roads, bridges, and tunnels, on the other hand, the critical factor is the induced traffic load effects for structural design and assessment (Barceló, 2010; Hoogendoorn and Bovy, 2001). Interestingly, in some newly proposed and improved traffic flow models, vehicles are apt to be classified in detail to present realistic traffic dynamics caused by vehicle types (Webster and Elefteriadou, 1999; Treiber et al., 2000; Chanut and Buisson, 2003; Bagnerini and Rascle, 2003; Wang et al., 2016). Trucks, analogously vehicle loads from another point of view, are gradually regarded as an important influence factor on vehicle behaviors (Treiber et al., 2000; Chanut and Buisson, 2003).

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Theoretically, as for vehicles of the same type and length, a heavy vehicle is generally conservative in lane-changing and apt to hold a larger safe headway and low velocity. Moreover, traffic loads are of considerable interest for the evaluation of infrastructures (Frangopol and Liu, 2007). It is found that heavy trucks are inclined to travel in a platoon, which is the main cause of bridge collapse (Shi et al., 2016). Hence, it is important to develop traffic simulation methods that incorporate loads to present the vehicle dynamics influenced by detailed information of type, length and load, and to generate traffic load sequences for accurate performance estimation of infrastructures.

In traffic engineering, microscopic traffic simulation addresses the behavior of individual vehicles and is flexible to dynamically produce adverse traffic phenomena, therefore, has received wide applications (Helbing et al., 2002; Hidas, 2005). Cellular Automaton (CA), an effective modeling method for a dynamic system with discrete time, space, and state, is a good fit for the inherent discrete characteristics of the traffic system, and has become a key tool (Bham and Benekohal, 2004; Kerner et al., 2011; Tian et al., 2014). The traffic cellular automata (TCA) are developed into two parts, deterministic traffic cellular automata (DTCA) and stochastic traffic cellular automata (STCA). STCA provide a more comprehensive description of the randomness of vehicles and have gained wider application. The initial STCA model was proposed by Nagel and Schreckenberg (1992) and is constantly validated to be consistent with realistic traffic phenomena (Maerivoet and De Moor, 2005).

For infrastructure such as bridges, the simulation of traffic loads is progressively focused along with available site-specific traffic data (Pelphrey et al., 2008; Ruan et al., 2016). Over the course of the lifetime of a bridge, there are many loading scenarios due to the high randomness of traffic loads. Therefore, where there is an inadequate quantity of traffic data, traffic load simulation is generally needed to account for the wide range of traffic loading scenarios that cannot be fully determined from measurements. Traffic load simulation for bridges, however, is quite different regarding the length. Short and medium span bridges have limited total length, and only numerable vehicles can be simultaneously packed. Generally, the micro-behavior of car following and lane-changing is essentially not that important (Enright and O'Brien, 2013). For long span bridges, however, the time it takes for a vehicle to pass through the bridge is considerable, during which the microscopic motions of acceleration, deceleration and lane-changing are inevitable, especially under adverse conditions such as lane closures, congestion and traffic accidents. These vehicle micro-behaviors dynamically change the spatial density and average velocity of the load sequences, resulting in different load effects. Hence, micro-simulation is necessary, but this is a relatively new area of research. O'Brien et al. (2012) and Caprani (2012) use the Intelligent Driver Model (IDM), developed initially by Treiber et al. (2000), to simulate microscopic congested traffic loading on long span bridges. This micro-simulation model of IDM is a vehicle based continuous approach, and can consider the precise vehicle's on-bridge location and microscopic behaviors. Meanwhile, Chen and Wu (2012) first introduced STCA, a space-based discrete approach, for the micro-simulation of traffic loads on long span bridges. In their work, the intact STCA models are applied with vehicle weight information embedded, which takes advantage of the dynamic and adaptive evolution of CA and is thus efficient. This approach significantly addresses the modest traffic loads for long span bridges (Wu et al., 2015). However, although the generated traffic states are realistic in STCA models, all vehicles are equal to a cell with united size of 7.5 m, and the vehicle lengths, gaps, and velocities are all integer multiples of the cell size, resulting in a crude vehicle gap and a simple concentrated force representing vehicle weight that ignores vehicle length.

This paper, based on STCA, proposes an improved cellular automaton with axis information, defined as the Multi-axle Single-cell Cellular Automaton (MSCA), for the precise micro-simulation of random traffic loads on long span bridges. In MSCA, the loading of a vehicle is redefined in the cells with precise axle positions, but only represented by its first axle occupying a single cell for traffic evolution; the cell size, time step, and vehicle velocity can be custom-made according to the calculation demands. Thus, vehicle axles' positions and realistic gaps, as well as detail vehicle lengths and velocities, can be incorporated, allowing for not only a precise loading of vehicle sequences on infrastructures but also an accurate basis for the microscopic traffic choice of vehicles. The simulation methodology of MSCA is then established. Finally, site-specific WIM data are used to calibrate and validate MSCA, and the generated traffic parameters and load effects (LEs) are compared with those from WIM data to demonstrate the rationality and accuracy of MSCA.

2. Background of cellular automata for traffic simulation

A CA is an efficient dynamic modeling method widely applied in traffic engineering and other fields (Sarkar, 2000). In the basic model of a CA, simulation space is divided into a lattice with clear boundaries, which are called cells. The parameters of the state transformation along with time and space are saved in the cells. "Automaton" refers to the parameters of cells' states that can be updated automatically in the time dimension according to the transition rules and neighbor cells. In a CA, four main ingredients of lattice, cells' states, neighborhoods and transition rules are important, as given by Eq. (1):

$$CA = (L^d, \sum, N, \delta) \tag{1}$$

where CA represents a cellular automaton system; L is the lattice, i.e., physical environment; superscript d represents the dimension of the lattice, which is a positive integer; $\sum$ represents the set of cells' states; N is the set of neighborhoods for a target cell; and δ is the transition rules. The relationships of the four main ingredients in a typical 2-dimensional cellular automaton are demonstrated in Fig. 1.