On Modeling and Verification of Agent-Based Traffic Simulation Properties in Alloy

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ABSTRACT
The advances in Intelligent Transportation Systems (ITS) call for a new generation of traffic simulation models that support connectivity and collaboration among simulated vehicles and traffic infrastructure. In this paper we introduce MATISSE, a complex, large scale agent-based framework for the modeling and simulation of ITS and discuss how Alloy, a modeling language based on set theory and first order logic, was used to specify, verify, and analyze MATISSE’s traffic models.

Keywords: Alloy, Formal Specification, Intelligent Transportation Systems (ITS), Multi-Agent Systems, Traffic Simulation, Verification

1. INTRODUCTION
For the past twenty years, Intelligent Transportation Systems (ITS) have been considered as possible solutions for traffic safety and congestion problems. An ITS is defined as “the application of advanced sensor, computer, electronics, and communication technologies and management strategies in an integrated manner to increase the safety and efficiency of the surface transportation system” (Meyer, 1997). The work presented in this paper is based on a novel, multilayered integrated ITS for safety improvement and congestion reduction (Boyraz et al., 2009a; Wenkstern, Steel, Daescu, Hansen, & Boyraz, 2009a). In this ITS infrastructure traffic is viewed as a bottom-up phenomenon that is the consequence of individual decisions at the micro-level, and traffic management as a top-down activity that is the result of decisions taken at the macro-level. Both macro- and micro-levels consist of multi-agent based infrastructures where autonomous traffic entities continuously communicate and interact with each other to achieve traffic safety and efficiency goals. Even though some of the
proposed ITS components have already been implemented, the overall infrastructure is still in its conceptual phase.

Given the critical role of interactions among ITS components and their independent decision making capabilities, it is essential to simulate traffic scenarios under nominal and extreme conditions before deploying the physical infrastructure on roads and highways.

MATISSE (Multi-Agent based Traffic Safety Simulation systEm) is an agent-based “tailor made” simulation framework designed to provide a platform for the execution of such scenarios. MATISSE provides means to analyze and evaluate different ITS configuration, collaboration, and control strategies. Before embarking on the full-scale development of this large-scale, distributed, multi-agent based simulation framework, the specification and validation of MATISSE’s properties proved to be necessary.

Alloy is a modeling language based on set theory and first order logic that has been used in both industry and academia to validate a wide variety of systems (Coppit & Sullivan, 2000; Dolby, Vaziri, & Tip, 2007; Jackson & Vaziri, 2000). The language has a simple and concise syntax that comes with a powerful, integrated tool for compiling and analyzing models.

The purpose of this paper is to present a formalization of the MATISSE model in Alloy, and discuss how the model’s core properties are verified using Alloy’s Analyzer. In particular, we discuss an approach to produce execution traces from the specification. These traces serve two purposes: they allow for a thorough analysis and evaluation of the traffic model; and demonstrate the suitability of MATISSE for the simulation of ITS scenarios.

In the following section we give an overview of traffic simulation systems. In Section 3 we briefly present the proposed ITS and MATISSE’s high level architecture. In Section 4 and section 5 we discuss how Alloy has been used to specify, verify, and analyze MATISSE’s model. In Section 6 we present an evaluation of the approach. Finally, in Section 7 we give an overview of related works.

2. TRAFFIC SIMULATION

There are two major approaches to simulate traffic scenarios. Macroscopic models (Babin, Florian, James-Lefebvre, & Spiess, 1982; Lieu, Santiago, & Kanaan, 1992) describe traffic as a physical flow of fluid and make use of mathematical equations relating macroscopic quantities (e.g., traffic density, flow rate and average velocity). These models assume rational driving behavior and fairly consistent traffic streams and thus are unfit to model real traffic operations.

In contrast, microscopic models consider the characteristics of individual traffic elements (e.g., vehicles, traffic lights, traffic signals, driver behavior) and their interactions. Typical microscopic models are based on analytical techniques such as queuing analysis and shock-wave analysis (Helbing & Tilch, 1998). They assume traffic elements with predefined behavioral models. This is a limitation since realistic traffic simulation scenarios call for the modeling of unexpected behavior and unforeseen environmental conditions. The multi-agent paradigm alleviates this limitation by providing means to address non-deterministic behavior in non-deterministic, unpredictable environments.

Over the last decade, a large number of agent-based traffic simulation systems have been proposed. Some focus on specific small scale traffic problems such as driver behavioral modeling, tactical driving, and intersection management (Dresner & Stone, 2008; Rossetti & Liu, 2005; Sukthankar, Hancock, & Thorpe, 1998) while others attempt to tackle complex large scale traffic scenarios (Balmer et al., 2009; Cetin, Nagel, Raney, & Voellmy, 2002; Galland, Gaud, Demange, & Koukam, 2009). In this section we restrict our discussion to those that best compare to MATISSE, namely MatSim (Balmer et al., 2009), and Transims (Cetin et al., 2002).

MatSim (Balmer et al., 2009) is an agent-based framework for modeling transport demand. MatSim represents individual travelers as agents endowed with predefined plans. These agents follow a utility based strategy to
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