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A generic multi-level framework for microscopic traffic simulation—Theory and an example case in modelling driver distraction

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ABSTRACT

Incorporation of more sophisticated human factors (HF) in mathematical models for driving behavior has become an increasingly popular and important research direction in the last few years. Such models enable us to simulate under which conditions perception errors and risk-taking lead to interactions that result in unsafe traffic conditions and ultimately accidents. In this paper, we present a generic multi-level microscopic traffic modelling and simulation framework that supports this important line of research. In this framework, the driving task is modeled in a multi-layered fashion. At the highest level, we have idealized (collision-free) models for car following and other driving tasks. These models typically contain HF parameters that exogenously "govern the human factor", such as reaction time, sensitivities to stimuli, desired speed, etc. At the lowest level, we define HF variables (task demand and capacity, awareness) with which we maintain what the information processing costs are of performing driving tasks as well as non-driving related tasks such as distractions. We model these costs using so-called fundamental diagrams of task demand. In between, we define functions that govern the dynamics of the high-level HF parameters with these HF variables as inputs. When total task demand increases beyond task capacity, first awareness may deteriorate, where we use Endsley's three-level awareness construct to differentiate between effects on perception, comprehension, anticipation and reaction time. Secondly, drivers may adapt their response in line with Fullers risk allostasis theory to reduce risk to acceptable levels. This framework can be viewed as a meta model, that provides the analyst possibilities to combine and mix a wide variety of microscopic models for driving behavior at different levels of sophistication, depending on which HF are studied, and which phenomena need to be reproduced. We illustrate the framework with a distraction (rubbernecking) case. Our results show that the framework results in endogenous mechanisms for inter- and intra-driver differences in driving behavior and can generate multiple plausible HF mechanisms to explain the same observable traffic phenomena and congestion patterns that arise due to the distraction. We believe our framework can serve as a valuable tool in testing hypotheses related to the effects of HF on traffic efficiency and traffic safety in a systematic way for both the traffic flow and HF community.

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1. Introduction

Incorporation of human factors (HF) in mathematical models for driving behavior has become an increasingly popular research direction in the traffic flow theory community the last decade. One may argue, however, that HF have always been at the core of traffic flow modelling. Since the pioneering work of (Greenshields, 1934,Lighthill and Whitham, 1955; Richards, 1956 and many others) on the fundamental relation and the fluid dynamical description of traffic, many schools of thought have emerged, each characterized by different behavioral assumptions on how drivers respond to stimuli—and which stimuli they respond to; and by different ranges of descriptive and (partial) explanatory power for the resulting phenomena. For example, safe-distance car following (CF) models (Laval and Leclercq, 2010a; Newell, 2002; Pipes, 1953) assume that drivers maintain a large enough distance headway in case the leader brakes at maximum deceleration; optimal velocity models (Bando et al., 1998; Davis, 2003) assume that drivers accelerate to their optimal velocity as a function of the distance headway; whereas approaches in the more general group of stimulus-response models (Gazis et al., 1961; Kerner and Klenov, 2006; Treiber et al., 2000) make assumptions on how drivers adapt their response (acceleration) to a range of different stimuli (distance headway, speed differences). Over the years, many approaches to incorporate more (HF) sophistication have been proposed. So-called psycho-spacing (or action point) models (Fritzsche, 1994; Wiedemann, 1974) incorporate drivers' inertia to observe and respond to small changes in stimuli; whereas for example multi-anticipatory models (Hoogendoorn et al., 2006,2007; Treiber et al., 2006) include terms for anticipation of drivers to traffic conditions further downstream. What "classic" (or as Saifuzzaman and Zheng, 2014) put it: "engineering" models) for car following (CF) have in common is that they are—by design—collision-free. This is no longer guaranteed, however, if we incorporate reaction times, i.e. delayed stimuli, and/or perception errors in these stimuli (headways, relative speeds) or both (Hamdar and Mahmassani, 2008; Treiber et al., 2006). An even wider diversity of behavioral assumptions and modelling approaches can be found for lateral driving behavior that governs when drivers change lanes, diverge, and merge (Choudhury, 2008; Cohen, 2004; Kesting et al., 2007; Laval and Daganzo, 2006; Schakel et al., 2012; Wei et al., 2000; Zheng, 2014). In most cases here, the underlying theory is based on conditional decision-making. The corresponding models usually incorporate decision trees, and models assessing the conditions (availability of gaps) and the appropriate response (intention and execution of crossings or lane changes). Also models for lateral driving are—in principle—collision free. Like CF models, the inclusion of reaction times and/or perception errors in lane changing (LC) models relaxes that assumption.

There are several good reasons why research has accelerated into more sophisticated and systematic approaches to incorporate HF in microscopic traffic flow models. First, there still are many phenomena in current traffic that we do not fully understand, such as the capacity drop, traffic hysteresis, and many phenomena related to lateral movement (Saifuzzaman and Zheng, 2014; Zheng, 2014). Second, we are at the start of a major transition towards higher levels of vehicle automation (VA). Paradoxically, traffic simulation models have always been capable of simulating automated vehicles; now that VA becomes a reality, we need to increase the HF sophistication in our human driver models. Since traffic flow operations are governed by interaction processes, we cannot predict the changes in those interactions and their consequences based on knowledge of the behavior of just one of the 'players' (the automated vehicle)—the human player may also fundamentally change in ways not catered for (sufficiently) by existing models. Third, whereas most emphasis of microscopic traffic modelling has been on reproducing safe traffic operations and the corresponding emerging phenomena (e.g. capacities, wave patterns), an increased need emerges to use these models to realistically predict also potentially unsafe traffic operations, and the corresponding indicators (statistics of accidents and surrogate safety measures) (Hamdar and Mahmassani, 2009; Hamdar et al., 2015b). These conditions are relevant not just in studying vehicle automation, but also in the here and now. To assess whether safety is at risk, explanatory psychological constructs are needed that can endogenously predict under which circumstances drivers take risks and/or make perception and judgement errors that may lead to unsafe situations and ultimately accidents. Several approaches have already been proposed in this direction, e.g. using prospect theory (in which drivers way faster travel time against the risk of rear-end crashes (Hamdar et al., 2015a, 2008); and using Fullers' Risk Allostasis Theory (Fuller, 2011) (in which risk taking and driver response is considered a result of comparing subjective task demand and task capacity using the so-called Task-Capacity-Interface model (e.g. Hoogendoorn et al., 2013; Saifuzzaman et al., 2015, 2017). However, more behavioral sophistication comes at a methodological and computational price, in terms of model identification, calibration and validation efforts; and computational efficiency. Therefore, the challenge for our community in the coming years, is to augment existing CF and LC models with a range of explanatory (HF) mechanisms that (a) endogenously predict where and under which circumstances drivers e.g. make errors, take more (or less) risks, suffer from longer reaction times; using (b) mathematics and simulation logic that is tractable and simple enough so that large-scale simulation is (still) possible; while (c) still reproducing plausible vehicle trajectories and (by implication) plausible macroscopic traffic patterns. There is an additional practical, but nonetheless important design criterion that relates to the (software) development of traffic simulation models. Such new additions to the already broad family of micro-simulation models need to find their way into both commercial (closed-source) (e.g. Casas et al., 2010; Fellendorf and Vortisch, 2009; Mahut and Florian, 2010; Sykes, 2010) and open-source (Krajzewicz et al., 2012; Treiber and Kesting, 2010; van Lint et al., 2016) traffic microsimulation packages. This requires a generic modelling framework that allows combination of different modelling approaches and implementations that are modular and maintainable.

The central contribution of this paper is such a generic multi-level modelling and simulation framework that supports this research challenge and that generalizes existing approaches to incorporate human factors in models for driving behavior. In this paper we focus on car following (CF) only, however, the framework can be naturally extended to support lane