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From behavioral psychology to acceleration modeling: Calibration, validation, and exploration of drivers' cognitive and safety parameters in a risk-taking environment

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ABSTRACT

We investigate a utility-based approach for driver car-following behavioral modeling while analyzing different aspects of the model characteristics especially in terms of capturing different fundamental diagram regions and safety proxy indices. The adopted model came from an elementary thought where drivers associate subjective utilities for accelerations (i.e. gain in travel times) and subjective dis-utilities for decelerations (i.e. loss in travel time) with a perceived probability of being involved in rear-end collision crashes. Following the testing of the model general structure, the authors translate the corresponding behavioral psychology theory – prospect theory – into an efficient microscopic traffic modeling with more elaborate stochastic characteristics considered in a risk-taking environment.

After model formulation, we explore different model disaggregate and aggregate characteristics making sure that fidelity is kept in terms of equilibrium properties. Significant effort is then dedicated to calibrating and validating the model using microscopic trajectory data. A modified genetic algorithm is adopted for this purpose while focusing on capturing inter-driver heterogeneity for each of the parameters. Using the calibration exercise as a starting point, simulation sensitivity analysis is performed to reproduce different fundamental diagram regions and to explore rear-end collisions related properties. In terms of fundamental diagram regions, the model in hand is able to capture traffic breakdowns and different instabilities in the congested region represented by flow-density data points scattering. In terms of incident related measures, the effect of heterogeneity in both psychological factors and execution/perception errors on the accidents number and their distribution is studied. Through sensitivity analysis, correlations between the crash-penalty, the negative coefficient associated with losses in speed, the positive coefficient associated with gains in speed, the driver's uncertainty, the anticipation time and the reaction time are retrieved. The formulated model offers a better understanding of driving behavior, particularly under extreme/incident conditions.

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1. Introduction

In 2008, an acceleration-based car-following model was proposed that incorporates the risk-taking attitudes of drivers and uses prospect theory to evaluate the perceived consequences of applying different acceleration rates, a probability of collision and a crash penalty term are explicitly introduced in the formulation (Hamdar et al., 2008). This paper builds on this approach while changing the fundamental equations previously suggested (i.e. subjective utility function) for exploring the characteristics of the formulated car-following model in terms of its ability to capture congestion regions, equilibrium characteristics, inter-driver heterogeneity and collective accident-prone behaviors on a freeway section. Being calibrated against real-life trajectory data (FHWA, 2004), different bottleneck and incident scenarios are modeled: bottleneck scenarios are tested via deceleration exerted by the leader and on-ramp merging; incident scenarios are tested via rear-end collision and fixed object crashes. Special interest is given to studying the resulting fundamental diagram especially traffic breakdown and the congestion disturbances. The effect of both psychological factors and execution/perception errors on the accidents number and their distribution along a freeway length is also studied. Through sensitivity analysis, insights into the relationships between the crash-penalty, the negative coefficient associated with losses in speed, the positive coefficient associated with gains in speed, the driver's uncertainty, the anticipation time and the reaction time are provided.

The objective of this research is to offer a stochastic fully dynamical acceleration model incorporating (a) traffic flow theory fundamentals (i.e. fundamental diagram), (b) findings of prospect theory on the form of the perceived (subjective, generalized) utility, (c) risk taking, (d) perception limits and subjective behavioral fluctuations. The model is supported by decision-making theories' concepts and safe/unsafe driving maneuvers are created as an inherent result of the utility function without imposing unrealistic safety constraints.

The first contribution of this research is capturing driver behavior in congested and situations while incorporating drivers' risk-taking attitude in the model equations. The model formulated in this paper does not exogenously impose safety constraints to prevent accidents. Models used in practice typically preclude accidents, contrary to real-life situations. One more implication of this contribution is capturing that drivers do not perfectly register existing stimuli without subjectively weighing different alternatives based on their personality (aggressive versus conservative drivers). This allows risky behavior as an inherent result of the model. Moreover, the corresponding acceleration choice emerges as a probabilistic decision making process facing uncertainty; the method by which the resulting accident causing behavior is weighed can be calibrated based on recorded traffic data. It should be mentioned that in the first and only published work on the related formulation (i.e. Hamdar et al., 2008), the formulation was not developed enough neither to derive the corresponding homogenous fundamental diagram nor to reproduce real-world trajectory data in different traffic conditions. In other words, the authors did not look beyond the acceleration probability density functions in different local scenarios (i.e. for specific relative velocities, spacing and initial velocities with non-calibrated model parameters). The resulting probability density functions were feasible and acceptable as drivers accelerated when they were supposed to accelerate and decelerated when they were supposed to decelerate. The logical steps beyond such preliminary findings and that are performed in this research work are to:

a. Expand the formulation and further test the corresponding car-following model in terms of the flow-density-speed macroscopic properties.
b. Utilize a suitable calibration methodology and make sure that the suggested model reproduces rear-world trajectories especially during congestion conditions.
c. Transform the model into an efficient simulation tool (possibly utilized for prediction and real-time evaluation purposes) and analyze the corresponding non-homogenous fundamental diagram (flow-density data points scattering).
d. Make sure that the resulting model does not produce the same non-realistic crash patterns observed in existing acceleration models if the corresponding safety constraints were relaxed. These non-realistic patterns were already analyzed in Hamdar and Mahmassani (2008).

The second and the third steps mentioned above are essential to be realized so the model may be useful for the traffic flow theory and traffic engineering communities. In other words, from a practitioner stand point, the main challenge in realizing the stated paper's objective while incorporating the corresponding parameters is the degree of complexity that would be added to the eventual model, which would preclude its usefulness in actual practice. Accordingly, another contribution of this research is to put forward a "logic" that is robust enough to advance the state of knowledge related to the driving task but simple and fast enough so that it can be readily implemented, calibrated and validated. The resulting model is intended to provide a competitive stochastic alternative to existing simpler models that lack cognitive dimensions.

In summary, the main challenge faced is translating the behavioral psychology prospect theory into a concise acceleration formulation given the importance of such structure for the calibration and the simulation exercise; this challenge is faced through the use of a Genetic Algorithm (GA) heuristic that allows calibrating the model for each "feasible" vehicle and attempting to capture a heterogeneity pattern. The structure of this paper will then follow; a background review on incidents and pertinent car-following models is presented in the following section. The framework of the work is shown in the third section where the corresponding car-following model is presented. The review and the framework will motivate testing the