Current Frontiers in Reproducing Human Driver Behavior

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Abstract
Most traffic simulation frameworks use sophisticated models to conceptualize human factors in traffic environments. In this work we want to find out in how far these approaches comply with models from human factor psychology—clearly the most advanced discipline, when it comes to the conceptualization of human behavior. Thus, we analyze common psychological models for human driver behavior and compare those with models that are actually implemented in contemporary traffic simulation frameworks. We discuss our findings and point out future research directions.

1. INTRODUCTION
Computer-aided traffic simulation frameworks became an indispensable tool for traffic planning and infrastructure management. Most simulation frameworks use sophisticated (frequently agent-based) models to mimic traffic- and transport systems in a lifelike fashion. Most works, however, are focused on the “physics” of such systems.

Human factors, such as driver behavior, are frequently neglected or only partially reflected. The reason for this is that human behavior is difficult to understand, to capture, and to formalize. Human behavior is highly individual and where one particular model fits for some characteristics, the same model may totally fail for others.

Nevertheless, there are some approaches that account for human factors. Most of these approaches use an agent-based model to formalize simulated drivers and traffic participants. Following Wooldridge and Jennings [1], autonomous, reactive, and proactive, as well as socially acting entities can be considered as intelligent agents. This description almost perfectly fits for (simulated) drivers, therefore developers apply the agent metaphor in order to make use of concepts, tools, and development methodologies from the very established agent-domain.

Despite the comprehensive support, the conceptualization of behavioral aspects remains difficult—not least because only few works connect psychological findings to traffic simulation models. In this work we aim to show how much psychology is implemented in contemporary traffic simulation frameworks. It is our objective to present the current state-of-the-art and to point out future research directions.

In order to do so, we introduce fundamentals of human driver behavior in Section 2.1. and continue by analyzing well established conceptualizations in Section 2.2. In this analysis, we identify factors that determine human driver behavior. Subsequently, in Section 3., we use these factors to determine the capability of contemporary traffic simulation frameworks to reproduce the distinct characteristics of human driver behavior. We discuss our findings in Section 4. and conclude our work in Section 5.

2. PSYCHOLOGY
Research in driver psychology goes back to 1938, when Gibson and Crooks [2] presented their approach, which explained the behavior of drivers by means of safety margins. There was much activity in developing models for human driver behavior, yet, the community somehow lost momentum in the 1970s.

The loss of enthusiasm was a surprise, especially in the light of the “cognitive revolution” that had swept human factor psychology at the same time [3, p. 485]. The reasons for this were not identified before 1986, when Michon [3] comprehensively analyzed and compared the capabilities of existing approaches. Based on this survey, Michon [3] concludes that available works were too much focused on the driver in a specific situation while the “bigger picture” was not considered. Michon [3] argues that drivers are constantly surrounded by a social as well as a technological environment and that any form of behavior can be considered as an interaction between the human being and such environment. In total, he identified four roles in which humans occur in traffic environments, namely: i) as an active road user ii) as a transportation consumer iii) as an active social being iv) or as a psycho-biological organism. Available approaches, however, were mostly focused on one role exclusively, ignoring factors from and dependencies to other roles.

To solve this problem and to account for the different roles in which humans occur in traffic environments, Michon proposed a new structure for driver behavior models—a hierarchical structure. This structure is referred to as the Hierarchical Control Model [3]. The Hierarchical Control Model can be understood as the beginning of our current understanding of human driver behavior.
2.1. The Hierarchical Control Model

It was Michon’s intention to describe human driver behavior as a result to factors that evolve from the traffic situation, but also account for factors that are not entirely related to the driving process, e.g. intentions, preferences, personality, or education, to name but a few. In order to do so, the Hierarchical Control Model [3] conceptualizes human driver behavior as a hierarchically ordered structure of different behavior levels. In total, the model distinguishes between three dimensions: The Strategic Level refers to the general planning stage of a trip. This stage includes the determination of trip goals, the route and the modal choice as well as a cost-risk evaluation. Furthermore, the behavior of drivers on this level is affected by general considerations about transport and mobility. Finally, concomitant factors such as aesthetic satisfaction and comfort are able to determine the outcome of this behavior level. Tactical Level or maneuvering level behavior refers to the ability of drivers to negotiate the directly prevailing circumstances. Maneuvers that are performed at this stage are largely constrained by the exigencies of the traffic situation, though, they have to meet the criteria that derive from the goals that were specified at the strategic level. Nevertheless, there are also cases where these goals may be adapted to fit the outcome of certain maneuvers. Examples for maneuvers that are performed at this stage are obstacle avoidance, gap acceptance, turning, and overtaking. Operational Level or control level traffic behavior refers to fundamental car controlling processes, such as controlling speed, following the road and keeping the vehicle on the road. Michon [3] identified the necessity to connect relevant model components, thus, he defined an interaction between the three levels of behavior. This interaction emphasizes the connection between the different levels of behavior, such that maneuvers that originate from a given level have to meet the criteria from the upper levels, but also allow the outcome of lower levels to change these criteria. The separate representation of hierarchically ordered levels of behavior became commonly accepted as a pattern for driver behavior models. Most contemporary works adopted this pattern and incorporate other factors, yet, the influence of the Hierarchical Control Level is still apparent. We continue by presenting well established models for human driver behavior.

2.2. Human Driver Behavior

The Hierarchical Levels of Driving Behaviour [4] model extends the Hierarchical Control Model by a fourth level of behavior. On the lowermost level, the Vehicle Manoeuvring level, drivers account for the controlling of speed, the vehicle’s direction and its position. On the Mastering Traffic Situations level, drivers adapt to the present traffic situation. On the third level, the Goals and Context of Driving level, drivers consider their purpose, their environment their social context and their company. The first three levels comply with the three levels that Michon proposed, yet, the connection between strategic level behavior and the driver’s environment is new. Finally, a fourth level, the Goals for Life and Skills for Living level was added at the top of the hierarchy. This level covers the area of personality and motives and allows to describe behaviors which are “less congruent with the norms of the society” [4, p. 18].

A similar approach was described by van der Molen and Bötticher [5]. The Hierarchical Risk Model for Traffic Participants [5] conceptualizes human driver behavior with the exact same hierarchy as the Hierarchical Control Model. In addition, the approach provides a concept for behavior alternatives and subjective probabilities and also accounts for perceptual, judgmental and decision processes of traffic participants at all levels of behavior. Furthermore, the model connects the drivers’ strategic level behavior to their environment. The transitions between the different levels of behavior were refined as well. Information flow between the driver’s Strategic level and Tactical level behavior is realized by so called Strategic Plans. Interaction between Tactical level and the Operational level behavior is done by so called Manoeuvring Plans.

Contrary to the first two approaches, the Matrix of Tasks [6] extends the Hierarchical Control Model not by further levels or more detailed specifications, but by an additional dimension. On the vertical axis, Hale et al. [6] use Michon’s levels of driver behavior. These levels, are “horizontally extended” by different levels of expertise and familiarity with the surrounding situation. The model also incorporates motivational aspects. Hale et al. [6] argue that the purpose and the importance of a trip may influence a driver throughout his journey. Contrary, situations which are encountered “en route” may trigger short term goals that motivate tactical problem solving and lead to the same outcome. Thus, the model allows motives to affect a driver’s decisions throughout the entire behavioral hierarchy. Similar to the Hierarchical Risk Model for Traffic Participants [7], the Matrix of Tasks connects the driver’s strategic level behavior to his perception.

A similar and also two-dimensional model was presented by Hatakka et al. [8]. The GADGET-Matrix [8] is based on the Hierarchical Levels of Driving Behaviour [4] which we presented above. The levels are horizontally extended by three categories of high-level aspects, namely: Knowledge and Skills, Risk-Increasing Factors and Self-Assessment. Knowledge and skills refer to routines and information that are required for driving under regular conditions, risk-increasing factors can be considered as traffic or life-related factors, which are associated with a higher risk. Finally, self-assessment describes the drivers’ ability to reflect their own driving skills and motivations. The hierarchical assembly emphasizes that decisions on the upper behavior levels may af-
fect low-level decision-making and vice versa. Furthermore, decision-making on each level is affected by: the driver’s attitude, his lifestyle, and personal values.

The next approach that we present is the *The Filter Model of Risky Behaviour and Road Accidents* [9]. Summala [9] assumed that at least three factors affect a human’s decisions simultaneously, thus, the model explains human driver behavior by means of three dimensions. On the first dimension, Michon’s original behavior hierarchy was used. On the second dimension, a functional taxonomy distinguishes between enclosed capabilities, such as lane keeping, headway control or obstacle avoidance. On the third dimension, three psychological processing levels were defined. Shortly after the model was published, Summala [10] identified the importance of motivational factors for human driver behavior. He extended his original work and presented the *Multiple Sieve Model* [10], which explicitly accounts for emotions and motives and allows both factors to affect the drivers’ behavior on each level.

The *DRIVABILITY* model [11] works differently than the models that we presented above. The model describes driving behavior as a result to five permanent and temporary contributors, which simultaneously affect a driver’s decisions. These contributors are defined as follows: i) *individual resources* are physical, social, psychological and mental conditions of the conceptualized driver, ii) *knowledge and skills* refer to the driver’s training, experience, and knowledge in general. The latter can be understood as basic education which influences a driver’s motivation and his behavior. Furthermore, this contributor comprises the driver’s self-awareness for his own skills, iii) *environmental factors* describe the driver’s environment. In addition to the status of his vehicle, this may also comprise traffic hazards, weather conditions, or the general traffic situation. Finally, iv) & v) *workload and risk awareness* are the two common denominators between the drivers’ resources and their environmental status. The drivers’ risk awareness is also influenced by other factors such as risk perception, the level of attention and, possibly, by driver support systems.

The *Adaptive Control of Thought-Rational*, or ACT-R [12] combines cognitive, perceptual and motor dimension and was developed to explain highway driving with moderate traffic. The ACT-R defines driver behavior by means of three different tasks, namely: to control, to monitor and to decide. The ACT-R does not account for different levels of behavior. The reason for this limitation is the focus of the ACT-R, which is exclusively on Operational Level behavior. Despite this focus, the model emphasizes that low level decisions are affected by personal attitudes and external factors. The ACT-R is one of the few models that conceptualizes the effects of driver-actions on their environment [13].

The *A Common Mental Environment-Driver Model*, or ACME-Driver Model [14], was inspired by the decision-making process of the real human brain and actually uses a similar structure. The model defines three different types of memories, namely the sensoric input register, the short-term memory and the long-term memory. The difference between these components is the time that collected information remains available. Following Tulving [15], the model subdivides the long-term memory into an episodic memory, which saves information about single situations from the human’s life, the semantic memory, which is used to save common or logically expressible rules such as rules of algebra and the procedural memory, which contains non-verbalizable information about movements. Similar to the ACT-R, the ACME-Driver model does not account for levels of behavior. Krajzewicz argues [14], that the model was not supposed to serve as a comprehensive driver conceptualization, but rather as a detailed description of Operational Level of behavior. Despite this limitation, the model emphasizes the importance of experiences and external factors on human driver behavior.

The *Contextual Control Model*, or COCOM [16] is based on Neisser’s perceptual cycle [17] and conceptualizes the driver and his environment as a Joint Cognitive System. The central concept of the COCOM is the Construct-Action-Event Cycle, which describes how drivers select actions based on knowledge or assumptions about the situation in which the action takes place. The model also conceptualizes affects of driver actions on the environment. The COCOM is limited to account for Strategic Level behavior only, though, an extension is available. The *Extended Control Model*, or ECOM [18, 19], extends the COCOM by a behavior hierarchy and thus accounts for cognitive decision processes on different levels of behavior. In total, four levels were defined, namely tracking, regulating, monitoring, and targeting. On the targeting level the driver sets general goals of the driving task. These goals are the input for the monitoring level, where the driver attempts to control the state of the joint cognitive system. On regulating level, the driver deals with conscious processes, such as keeping desired safety margins to other traffic elements. Finally, on the tracking level, the driver compensates external disturbances, such as wind gusts.

Above, we presented a selection of the most commonly used driver behavior conceptualizations. We conclude this section by compiling a list of distinguishing characteristics of human driver behavior.

### 2.3. Inferences

To start with, most approaches conceptualize human driver behavior as a hierarchically ordered structure. Some works adopt Michon’s hierarchy [3], others define additional levels, yet others focus on selected levels but explicitly argue that— for a more comprehensive consideration of human driver behavior—additional levels are required.
Beyond the distinguishing structure, we are able to identify several other factors that affect human driver behavior. To start with, a driver’s behavior is somehow connected to his environment, such that changes in this environment cause drivers to adapt their behavior. Furthermore, a driver’s decisions are determined by his experience or knowledge. Goals or motives (also the purpose) are important and so is the driver’s personality—his attitude. Other factors that determine human driver behavior are: emotions, the capability to self-assess and the driver’s workload. We compare the expressiveness of all presented models in Table 1.

We proceed by analyzing the capabilities of traffic simulation frameworks to account for the psychological understanding of human traffic behavior.

3. SIMULATION

As long as vehicles are not controlled autonomously, traffic is significantly determined by human factors. Developers of traffic simulation frameworks account for this and include sophisticated models to mimic human decisions. In this section we show in how far these models align with the “psychological understanding” of human behavior in traffic environments. To provide some structure to this section, we use those factors that we identified as determining characteristics of human driver behavior as categories and respectively present simulation frameworks that account for these factors.

Levels of Behavior: All analyzed traffic simulation frameworks [14, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32] include models for Tactical Level driver behavior. In the most cases, these models belong to the category of stimulus-response models, such that certain events cause drivers to change their behavior (e.g. accelerate, decelerate, change lane, use exit, etc.). There are only few approaches available that account for higher behavior levels.1 The most popular works with support for Strategic Level behavior are MATSim [23], SUMO [14], and FEATHERS [33]. MATSim uses an agent-based approach to conceptualize driver behavior [34]. The simulated world comprises a physical layer, where agents move and avoid each other and a mental layer, where agents generate strategies such as routes, mode choices and daily activity plans. MATSim is able to simulate individual route choices and the avoidance of congested road sections. The Simulation of Urban Mobility, or SUMO framework [14], is mainly focused on Tactical Level behavior, yet, simulated drivers are able to compute individual routes and to avoid congestion during the simulation—clearly strategic level features. FEATHERS [33] comprehensively accounts for strategic level behavior. In fact, FEATHERS is an activity generator rather than a traffic simulation framework. It produces activities that can be used to generate the demand for traffic simulations. This production process is agent-based and comprehensively accounts for strategic level traffic behavior in that activities are planned, re-arranged, and optimized with respect to several factors.

We are not aware of any simulation framework that accounts for Control Level behavior.

Perception: All examined approaches [14, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32] account for an interaction between the driver and its environment on the Tactical Level. Those approaches that account for Strategic Level behavior [23, 33, 35] account for such connection as well.

Experience: There are some approaches that account for experiences. MATSim [23], FEATHERS [33] and Dynamic Route Assignment Combining User Learning and Microsimulation, or DRACULA [32], respectively use old activity schedules for the computation of new ones. Dynamic Network Assignment for the Management of Information to Travelers, or DynaMIT [36] uses the driver’s experiences for the computation of routes.

Motives: Motives can be considered as goals, or targets. Most traffic simulation frameworks simulate vehicles from a given source to a given target location, thus, we conclude that most traffic simulation frameworks implement the concept of motives.

Personality: There are several approaches that account for individual personalities. Champion et al. [26], Paruchi et al. [27], and Ehler at al. [20] allow for a custom- and individual specification of driving styles. FEATHERS [33] accounts for more detailed properties like age, gender, vehicles per household, or population density and produces highly individual activities.

Emotions: There are some approaches—all agent based—that account for emotions. Champion et al. [26], Paruchi et al. [27], and Ehler at al. [20] allow for a specification of driving styles. In doing so, all three approaches are able to mimic different types of emotional states, such as “aggressive”, “normal”, “in a rush”, or “cautious”.

Assessment: The only approach that conceptualizes self-assessment is SUMO [35]. Self-assessment is directly included into the car-following model and reflects the driver’s imperfection to maintain a desired velocity.

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1 In fact, there are many frameworks that account for elements of strategic-level behavior, e.g. to search for a parking lot or to find an initial route. Yet, we only focus on works with a comprehensive model for Strategic Level traffic behavior.
Table 1. The capabilities of commonly used driver behavior models. The left column shows the name of the author. The right columns indicate the model’s support for the respective feature. Control Level, Tactical Level, and Strategic Level behavior are abbreviated by their first letter, while “h” is short for “higher-level” behavior.

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Workload: There are no approaches that conceptualize the driver’s workload.

We compare the capabilities of all analyzed traffic simulation frameworks in Table 2 and proceed by discussing our results.

4. DISCUSSION

When looking at contemporary traffic simulation systems, one can clearly see that the importance of human factors has been recognized. Most works include human factors, yet, the focus of these representations is mostly on Tactical Level behavior. Admittedly, Tactical Level behavior has the most significant impact in scenarios in which computer-aided traffic simulation are most commonly used. Nevertheless, the analysis of psychological driver conceptualizations showed that factors from other levels of behavior may affect Tactical Level decisions. We conclude that there are only few approaches available [23, 33, 35] that connect Strategic Level aspects to Tactical Level problem solving. Furthermore, we conclude that contemporary works completely neglect Control Level behavior and higher levels of behavior.

All examined approaches account for factors that affect a driver’s decisions. These factors were also identified by psychological works, such that traffic simulations do not account for disturbances that psychology does not account for.

The first factor that is supported by all examined approaches is perception. Approaches that account for Tactical Level behavior mostly conceptualize perception as the driver’s awareness for the distance to the vehicle in front and vehicles in neighbor lanes. Approaches that account for Strategic Level behavior account for a connection between decisions on this level and the driver’s environment as well.

Some traffic simulation frameworks allow their drivers to “learn” and thus account for the second factor that we identified, namely experiences. Approaches that account for experiences usually simulate fixed time periods (e.g. hours or days) and iterate until the overall simulation terminates. From one simulation interval to the next, simulated drivers learn the effectiveness of their actions (e.g. routes or activity scheduling) and use this knowledge to determine actions in future intervals. Given the importance of experiences in traffic, it is a surprise that only few simulation frameworks account for such concept.

All analyzed approaches implement a concept for motives. Given that motives can be understood as the driver’s intention to reach a goal, this is not much of a surprise, but rather the fundamental concept of a traffic simulation. Yet, what human factor psychology actually refers to by mentioning motives as a factor for human decision making is the driver’s intention (or motivation) to reach a target location. In fact, there are no approaches available, where drivers consider their profit in arriving somewhere (and in refusing to do so). Such model implies an agent-oriented view and some form of behavior-engineering, e.g. Belief-Desire-Intention [37].

There are a few works that account for personality, all of them agent-based. While Ehlert et al. [20], Champion et al. [26], and Paruchi et al. [27] allow for a custom specification of driving styles for each simulated driver, FEATHERERS [33] allows for a more detailed specification of the drivers’ personality, e.g. age, gender, vehicles per household, population density, and even the occurrence of shops in the neighborhood of the driver.
Table 2. Capabilities of contemporary traffic simulation frameworks.

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Approaches that account for emotions are similar to those that account for personality. This is no coincidence since these approaches (apart from FEATHERS [33]) allow for an individual specification (personality) of emotions for each simulated driver. Simulated emotions are reflected by varying driving styles, e.g., aggressive, normal, in a rush, or cautious, to name but a few.

There is only one approach that accounts for the capability of drivers to assess their actions, namely SUMO [35]. We explain this underrepresentation with the little expressiveness for a traffic simulation, yet, it has to be mentioned that most psychological works account for this factor. We conclude that the impact of self-assessment as a behavioral capability of simulated drivers should be analyzed in more detail.

Finally, there are no works that account for the driver’s workload. As opposed to self-assessing capability, this factor is also underrepresented in psychological works, thus, we conclude that the impact on traffic systems is negligible.

5. CONCLUSION

In this work, we analyzed the capability of contemporary traffic simulation frameworks to account for factors that human factor psychology identifies as determining characteristics of human driver behavior. We began by presenting the Hierarchical Control Model [3], the foundation for most contemporary driver models that are used in human factor psychology. Subsequently, we presented the most common driver conceptualizations and respectively identified factors that determine (or affect) human decision-making processes in traffic environments. We continued by analyzing common traffic simulation frameworks and respectively identified their capability to account for those factors that psychological works identify as significant for the outcome of human decision-making processes. Subsequently, we discussed our results.

Human factors are clearly represented in most available solutions, yet, we think that more comprehensive support for Strategic Level behavior is required. Only three out of fifteen approaches accounted for such form of behavior. Control Level behavior is completely neglected, though, a more comprehensive representation would not increase the expressiveness of those traffic simulations that we analyzed.

There were only few approaches that account for experiences of drivers. Experiences, however, have a significant impact on Tactical and Strategic Level decisions, thus, we conclude that additional research and more comprehensive simulation models are required.

There is also a clear underrepresentation of what psychology refers to as motives (for a more details refer to Section 4.). The impact of psychological motives for traffic simulations is not entirely clear, yet, due to the importance of motives in psychological works, we recommend to analyze the capabilities of such concept for traffic simulations as well.

Furthermore, there are only few works that account for individual behavior specifications and emotions. Most examined simulation frameworks facilitate large-scale simulations, including thousands of vehicles—individual traits appear to be negligible. Nevertheless, reality shows that individual drivers do have a significant impact on traffic systems, thus, there should be more research about the impacts of individual behavior on larger traffic systems.
Finally, there are only few works that account for self-assessment and the driver’s workload. While the latter is even underrepresented in psychology, the former is frequently included. Since the benefit of self-assessment for computer-aided traffic simulations is difficult to assess, we conclude that further research is required here as well.

REFERENCES


