A Generic Simulation Model for Strategic Level Driver Behavior

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ABSTRACT
When it comes to road traffic, there seems to be no parameter more essential than the driver himself. Currently, there are many models available, which can be used to describe a driver’s behavior for a traffic simulation. Nevertheless, despite the rich offer of available formalisms it is our opinion that existing approaches do not comply with psychological models. In this work we determine the differences between both domains and present a model which aims to bridge the gap between psychology and simulation.

Author Keywords
Traffic simulation; driver behavior; driver psychology; human factors.

ACM Classification Keywords
I.6.1 Distributed Artificial Intelligence: Intelligent agents

1. INTRODUCTION
As research in computer aided traffic simulations goes back to 1955 [40], many applied algorithms and simulation frameworks feature a high level of sophistication. Commonly, physics of motion or fluid dynamics are applied in order to predict a traffic participant’s movements. Yet, as a matter of fact, our traffic and transport systems are significantly determined by human factors and the question what actually happens on the road is not only determined by physics of motion, but also by the perception and attitudes of the drivers and external conditions.

Today, there are many approaches that represent human driver behavior in traffic simulation frameworks. The focus of these approaches, however, is mostly on what psychologists refer to as tactical level behavior. Higher-level aspects which are referred to as “strategic level driver behavior” [27] are either neglected or implemented in a far too specific fashion in order to reproduce the flexibility of human beings in traffic environments.

This paper aims to present strategic level driver behavior from a psychological point of view and to identify factors that affect its outcome. We approach this objective by analyzing the most common and established psychological driver behavior conceptualizations in Section 2. Based on this survey, we determine to what extent contemporary traffic simulations implement the “psychological understanding” of human strategic level driver behavior. In more detail, we aim to identify discrepancies between rather flexible psychological models and those rather static models that are implemented in contemporary traffic simulation frameworks (see Section 3). In Section 4 and Section 5, we address these discrepancies by presenting a simulation model, which is able to reproduce human driver behavior in compliance with psychological works and thus increases the expressiveness of available approaches. Finally, in Section 6, we present applications of our model and conclude our work.

2. PSYCHOLOGY
Psychological research in human driver behavior has a long history. In fact, the first work dates back as far as 1938, when Gibson and Crooks [13] introduced the concept of safety margins. Given this comprehensive background, it is surprising that there were only few attempts to implement psychological findings in a traffic simulation environment.

In this section, we introduce the concept of strategic level driver behavior form a psychological point of view and present the most relevant approaches to conceptualize this particular form of behavior. The aim is to identify a list of factors that affect human strategic level driver behavior and to use this list to determine to what extent contemporary traffic simulation systems comply with the psychological understanding of human driver behavior.

2.1. Strategic level driver behavior
Despite the fact that human factor research in driver behavior dates back to 1938, the concept of strategic level behavior, or more generally the distinction between different levels of driver behavior is relatively new. The “need” to distinguish between different levels of driver behavior was motivated by Michon [27], who characterized drivers as “goal oriented” or “intentional” systems after Dennett [9]. Michon further argued that drivers are compelled to their goals; a concept which commonly known as the single-minded principle [8]. In order to conceptualize human driver behavior, Michon proposed [27] a hierarchically ordered structure of three different behavior levels, namely operational behavior, tactical behavior, and strategic level behavior. Michon argues [27] that each level of behavior has different objectives and different time...
frames. Using Michon’s work, it was finally possible to explain certain traffic incidents, which were not explainable by available (mostly monolithic) models.

His original definition of strategic level driver behavior was only slightly adapted over the years. Following Michon [27], strategic level driver behavior 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.

Most contemporary approaches conceptualize strategic level driver behavior in compliance with Michon’s notion. I continue by presenting these approaches in more detail, respectively identifying factors that determine the outcome of strategic level decision-making processes.

### 2.2. Contemporary works

Two approaches, which are similar to Michon’s original model are the Hierarchical Levels of Driving Behaviour, presented by Keskinen [19] and the Hierarchical Risk Model for Traffic Participants [38], presented by Molen and van der Böttcher. Both works use a hierarchically ordered structure and distinguish between different levels of behavior. In both models, strategic level behavior is located at the top of the hierarchy, respectively connected to the lower level (which indicates that there is a connection between short(er) term decision-making and strategic level decision-making) and to the drivers’ environment. Both approaches [38, 19] consider the driver’s individual personality as a factor for the outcome of strategic level decision making and argue that such factor can be represented by means of a tailored utility function.

While the above-presented approaches comply with Michon’s original model structure, there were other works that extended the one-dimensional structure by further dimensions. To start with, the Matrix of Tasks [14] uses a second dimension, a “horizontal dimension”, in order to distinguish between different levels of expertise and familiarity with the surrounding situation. The GADGET-Matrix [15] defines a second dimension as well, however, in this case, the additional dimension is used to account for three categories of high-level aspects, namely: Knowledge and Skills, Risk-Increasing Factors and Self-Assessment. The Extended Control Model, or ECOM [17, 11], conceptualizes the human driver behavior as a hierarchy as well. Again, strategic level driver behavior resides at the top of the hierarchy. In the case of the ECOM, the strategic level decision making is conceptualized as Construct-Action-Event Cycle after Neisser [28], such that driver and his environment as a Joint Cognitive System. All above-presented models conceptualize human behavior as a hierarchically ordered structure of different levels of behavior. Strategic level behavior is respectively located at the top of the hierarchy and affected by the lower behavior level as well as by the drivers’ (awareness for) their environment. Finally, personality is considered as a significant factor for the outcome of human strategic level decision making in traffic environments.

In addition to the above-presented one or two dimensional driver behavior conceptualizations, there are also approaches that conceptualize human driver behavior by means of multi-dimensional structures. The Filter Model of Risky Behaviour and Road Accidents [35], for instance, conceptualizes human driver behavior by means of three dimensions. On the first dimension, Michon’s original hierarchy is used to distinguish between different levels of driver behavior. On the second dimension, a functional taxonomy distinguishes between enclosed capabilities. Finally, on the third dimension, three psychological processing levels were defined. Due to its success, the model was extended to the Multiple Sieve Model [36], which additionally accounts for the personality of the driver on each level of behavior.

The above-presented works conceptualize human driver behavior in its entirety. However, there were also approaches that particularly focused on strategic level behavior. The DRIVABILITY model [2] conceptualizes strategic level driver behavior as a result to five permanent and temporary contributors, which permanently affect a driver’s decision, namely individual resources, knowledge and skills, environmental factors, workload, and risk awareness. Individual resources can be considered as the driver’s personality. Hierarchical approaches conceptualize the workload as well, in this case, however, the factor evolves directly evolves from the lower levels of behavior. Being a one-dimensional model, Bekiaris et al. [2] had to include this factor somehow. The Adaptive Control of Thought-Rational, or ACT-R [34] and the A Common Mental Environment-Driver Model, or ACME-Driver Model [21] are also well-established driver behavior conceptualization. Their focus, however is on tactical behavior rather than on strategic level.

### 2.3. Factors

Presented approaches show that human strategic level driver behavior is seen as a decision-making process, which is determined by (at least) four factors. First, the driver’s decisions can be affected by the outcome of lower level decision-making processes. This dependency is reflected by the hierarchical structure of most presented approaches or by a permanent contributor in the DRIVABILITY model. Secondly, strategic level decision-making is determined by the drivers’ experience or their skills. Thirdly, the drivers’ personality is relevant for the outcome of strategic level decisions, and finally, the drivers’ environment is able to affect these decisions as well.

Now, having a better picture from the nature of strategic level driver behavior and knowing factors that determine its outcome, it is possible to have a look into contemporary traffic simulations and to determine to what extent these simulations reflect the (psychological) understanding of human strategic level driver behavior. In the following section, we analyze the most common and established traffic simulation frameworks in order to answer this question. In doing so, we focus on microscopic approaches due to the fact that we are interested in individual (driver-)behavior models.
3. TRAFFIC SIMULATION SYSTEMS

Today, there are many highly sophisticated traffic simulation systems available. Most of these programs implement models for human driver behavior, yet, the focus of these models is mostly on tactical level behavior, while only parts of strategic level decision-making are included (e.g., route-planning, or congestion avoidance). Furthermore, the implementation of factors that determine the outcome of strategic level planning is not in compliance with psychological works. We explain these discrepancies in the following.

3.1. State of the Art

There are only two approaches, which implement a holistic model of human strategic level driver behavior, namely MATSim [5] and FEATHERS [3]. Both frameworks conceptualize drivers by means of the agent metaphor, such that simulated drivers are modelled as (autonomous) agents. Furthermore, both approaches are activity-based approaches. In more detail, this means that each simulated agent receives a set of activities the agent has to accomplish throughout the simulation time. In order to accomplish the list of activities, the agent computes a plan, which meets the requirements that are given by the activities. A plan consists of the agent’s intended schedule of activities for the day and the travel legs that connect these activities. A leg specifies several attributes, e.g., departure time, expected arrival time, and the intended route or transportation mode. MATSim and FEATHERS are based on the user equilibrium, that is, the simulation is done under the assumption that (simulated) drivers aim to maximize the efficiency of their travel plans. In both cases, the procedure is implemented by means of evolution strategy (see e.g., Rechenberg [32]), an iterative, stochastic optimization mechanism. Both, MATSim and FEATHERS account for external factors, the drivers’ personality, and their experience. Factors that evolve from the outcome of lower behavior levels are not included, yet, there are some psychological works [38, 14, 36, 2, 17], which substantiate that it is possible to neglect the impact of a driver’s tactical level decisions and to consider strategic level behavior in isolation.

In addition to the above-presented approaches, which particularly account for strategic level behavior, there is a large number of approaches, which implement the one or the other strategic level capability.

The Simulation of Urban Mobility (or SUMO) framework [20], for instance, simulates driver behavior in compliance with the ACME-Driver Model [21] (see also Section 2.2.). The model is able to produce elementary forms of strategic-level behavior, such as individual routing capability or the ability of drivers to recognize high congestion and use alternative routes. Simulated drivers recognize congestion, therefore the framework defines a connection between the simulated drivers and their environment. A more comprehensive perception mechanism is not implemented. Drivers, for instance, are not able to perceive weather conditions or the infrastructure which surrounds them. Another framework capable to reproduce a particular form of strategic level driver behavior is VISSIM [12]. VISSIM is able to simulate the search for a parking lot—a strategic level planning capability.

In doing so, VISSIM directly connects the drivers’ decision-making to their environment. A similar feature is implemented by Paramics [37]. Other approaches, such as MIT-SIMLab [4] or Aimsun [6] equip their drivers with sophisticated route-finding mechanisms, such that drivers are able to avoid congestion and even to compute intermodal routes. Both approaches connect the drivers’ perception to their environment, making them able to recognize bus, metro, or train stops. Other approaches implement a connection between the drivers’ and their awareness for the current weather condition, e.g., AVENUE [22], Kyte et al. [23], or Rigolli and Brady [33]. These effects mostly affect the driver’s tactical level behavior, yet, the route choice mechanisms of all three approaches processes this information as well.

There are also approaches that account for the attitudes and the emotions of the drivers. The SCANeR II simulator [7], for instance, conceptualizes drivers as agents and is able to mimic “unique” or “risky” driving behavior. Paruchuri et al. [29] use micro and macro goals for the realization of different driving styles, such as “aggressive”, “normal” and “cautious”. A similar approach is described by Ehler [10]. All three models for attitudes and emotions, mainly affect the drivers’ tactical level behavior, yet, the route choice mechanisms of all three approaches processes this information as well.

3.2. Implication

Wrapping up, we can say that contemporary approaches generally account for strategic level driver behavior. Support, however, is not entirely in compliance with the psychological point of view.

Comprehensive strategic level decision-making models are implemented by MATSim and FEATHERS. Both approaches are focused on strategic level behaviour only, that is, tactical level behavior is not used as a factor. In fact, several psychological approaches [38, 14, 36, 2, 17], show that this approach is actually valid.

Both, MATSim and FEATHERS account for those factors that psychologists deem to be relevant for the outcome of strategic level decision-making, yet, both approaches are based on the assumption that drivers aim to optimize their actions in traffic and transport systems, a concept, which is commonly known as user equilibrium. On a large scale, this is a reasonable assumption! Drivers generally try to be as effective as possible—thus, on urban dimension, the approaches provide reliable results. Yet, human beings are not free from error and the impact of this “feature” becomes more significant, the more one wants to go into detail. If, for example, one wants to focus on selected infrastructure parts, e.g., a particular metro station with park-and-ride facility, MATSim and FEATHERS loose their precision, since some drivers favour e.g., comfort or safety over efficiency. As an example, consider an novice driver that happens to pass a metro station just when the weather situation drastically changes (e.g., sudden freezing rain or heavy snowfall). There is a good chance that this driver actually decides to change his mind and to use the metro instead of risking an adventurerous trip—even if this
means that the driver arrives later at the intended target location. Available approaches are not able to reflect this kind of “ad-hoc behavior” due to their basic assumption (the user equilibrium). Those approaches, which are not implemented in compliance with the user equilibrium, are generally able to account for such situations, yet, their strategic level decision-making models are not as comprehensive as in MATSim or FEATHERS. In most cases, strategic level decisions are represented as a result of one or two factors, thus, it is not possible to do analyses in compliance with psychological findings.

Based on the above-presented analysis, we argue that it is necessary to develop a model, which is not based on the assumption that drivers behave in an optimal fashion, and which conceptualizes strategic level driver behavior as a combination of the drivers’ experience, their skills, their personality, and their awareness for the surrounding environment. In the following section, we present such a model.

4. INFRASTRUCTURE

In total, there are three factors that we have to deal with, namely the drivers’ environment, their personality, and their experience. The latter two factors are parts of the driver, so we include both into the driver model (see Section 5) and start by presenting a model for the drivers’ infrastructure, their environment.

We distinguish between two categories of factors that evolve from the drivers’ environment, namely Infrastructural Features and Regional Conditions. Following Lützenberger et al. [26], an “Infrastructural Feature is everything which is able to fulfill a desire (or parts of it) of a person at a certain location of an infrastructure”. Based on this definition, Infrastructural Features are options or alternative ways which support a driver in achieving a particular goal. As an example, consider public transport. Public transport provides a service at many places of an infrastructure and supports a person’s desire to reach a certain location. According to our definition, a place where public transport service is offered can be considered as Infrastructural Feature as well.

A Regional Condition, on the other hand, “is everything which can affect or influence a person, its behaviour, or its vehicle (physically) at a certain location of an infrastructure” [24]. Regional conditions describe sources of irritation which have some kind of effect on a driver or his vehicle. The nature of this effect is either physical and psychological. Physical influences directly affect a driver or his vehicle. The driver has no alternative but to accept the effects until the affected area is left. By contrast, the results of psychological effects are individual as it is usually up to the driver on how he reacts on different irritations. As an example consider the effects of extreme and freezing rain respectively. On a physical level, both conditions have a similar effect. Extreme rain may compromise the vision of a driver and also increases his breaking distance. Freezing rain does not affect a driver on visual level, but increases his breaking distance (more severely).

We consider both factors as similar enough to define both with the same formalism. We allow for a specification in compliance with the following characteristics:

4.1. Locations

While Infrastructural Features are immovably anchored at a distinct position, Regional Conditions may be located either on a single position or comprise entire areas. Traffic simulation frameworks move vehicles either on existing or fictitious maps. For realistic results, we can assume that these maps are based on geographic coordinates and can be represented as GPS Exchange Format (GPX)\(^1\) data. To support not only distinct positions, but also “areas of influence”, or scopes, we extend GPX by an additional attribute which expresses the range of the respective influence. We define the location \(l\) of an influence \(i\) as follows:

\[
l := (i.pos, i.scope), \text{ where } i.pos \in \text{GPX}, i.scope \in \mathbb{R}
\]

We refer to the set of locations as \(L\).

4.2. Preconditions

For Regional Conditions, the situation is simple, as there is no precondition to sense environmental influences. Infrastructural Features on the other hand require such a specification. Consider again the car park example. To provide its service, a car park has to feature at least one vacant parking lot. Further, the driver has to be in possession of a vehicle. For the specification of preconditions we use first order predicates. A single precondition can thus be considered as predicate which either becomes true or false. As most influences require more than one precondition, we allow for this as well and define the preconditions \(p\) of an influence \(i\) as a set of predicates, to which we refer by \(i.pred\). We refer to the set of preconditions as \(P\) and further define that a driver \(d\) is able to make use of an influence \(i\) if the influence’s preconditions are satisfied. For this we define the \(canUse\) method, which complies with:

\[
\text{canUse}(i) : X \rightarrow \text{Boolean}, X \subseteq P
\]

4.3. Effects

Effects define an estimated target state which applies after the stimulus has affected the driver. This estimation can be used by the drivers in order to determine if the alternative option is viable or not. In case of the Infrastructural Features, these effects can be used by the agents to measure if it helps reaching the potential target state and whether to make use of it or not. In case of the Regional Conditions, the influence affects the driver without his agreement. We define effects as a set of functions which either manipulate the driver’s or an Infrastructural Feature’s attributes.

\[
e := \{ f \mid f : X \rightarrow X, X = D \text{ or } X = I \}
\]

We define \(D\) as the set of drivers, \(I\) as the set of applied Infrastructural Features and \(E\) as the set of effects. Further, we use

\(^1\)http://www.topografix.com/gpx.asp
\( e.f_i(d) \) in order to describe that the effects of an influence \( i \) are applied on a driver \( d \), such that \( d' = e.f_i(d) \).

### 4.4. Duration

Finally, we define a duration method for each influence, which is used by the simulation engine to determine the time \( t \) after which the effects of the influence occur. For Regional Conditions, this function is rather simple, as their effects occur immediately. For Infrastructural Features, this function can be highly complex and involve many parameters. We assume a specification of \( \text{dur} \) for an influence \( i \) to be in compliance with:

\[
dur : x_1 \times \ldots \times x_n \rightarrow \text{Time}, n \in \mathbb{N}, x \in \text{i.attributes} \quad (4)
\]

where \( \text{i.attributes} \) defines the set of attributes of an influence \( i \). We refer to the set of duration functions as \( \text{Dur} \).

So far, our definition fits purposes, however, more complex influence “systems” can not be captured, yet. A subway service for instance provides access at many distinct entrances, while the entire system is somehow interconnected. For this reason, we extend our model from single occurrences to complex systems.

### 4.5. The Stimuli System

We define a Stimuli System as follows:

\[
\mathcal{S} := \{(l, p, e, \text{dur}) | l \in \mathcal{L}, p \in \mathcal{P}, e \in \mathcal{E}, \text{dur} \in \text{Dur}\} \quad (5)
\]

We refer to the set of applied Regional Conditions as \( \text{Reg} \), such that:

\[
\mathcal{I} \subseteq \mathcal{S} \text{ and } \text{Reg} \subseteq \mathcal{S} \text{ and } \mathcal{I} \cap \text{Reg} = \emptyset
\]

Based on the given formalism, it is possible to include environmental influences which comply with our understanding of Regional Conditions or Infrastructural Features into simulation topologies. In the following we present a driver model.

### 5. DRIVER MODEL

In order to make our approach work, the driver model has to be able to comprehend influences which evolve from the model we have specified before. Following Michon [27] (see also Section 2.1.), drivers are intentional systems and their behavior complies with the single-minded principle after Cohen and Levesque [8]. The drivers’ characteristics allow for a formal specification in compliance with the BDI model after Rao and Georgeff [31]. To make this approach work, (simulated) drivers have to be considered as autonomous agents [39].

The appliance of BDI directly addresses one of the requirements that was identified when analysing psychological literature, namely support for experience and skills. BDI accounts for this concept by equipping agents with a belief base as well as with the capability to do reasoning operations on this belief base. Thus, the concept of experience and skills can be easily included by providing a fitting specification for the agents’ belief revision phase. The overall operation principle and behaviour phases of our BDI agents are illustrated in Figure 1.

![Figure 1. Architecture and actuation principle of our driver agents.](image)

Altogether, the agent’s execution cycle comprises four phases. Triggered by his perception (1), the agent starts with the Belief Revision, in which he updates (3) his belief base with his current perception (2a) and his current beliefs (2b). With his updated new belief base (4a) and his current intentions (4b), the agent updates (5) his current set of goals in the Generate Options phase. In combination with the agent’s plans and his current intentions, the new set of goals constitutes the input (6a, 6b, 6c) for the Filter phase, which generates (7) a new set of intentions. Finally, the new set of intentions is used (8) to determine the agent’s Action, by which he influences (9) his environment. In more detail, the different phases look as follows:

### 5.1. Prerequisites

In order to make this approach work, we define a set of required basic capabilities (or, using the BDI terminology “plans”) for each agent. Each driver has to provide a walk and a drive plan, which the agent uses to either walk or drive from a location A to a location B. In addition, we need some additional information on the usage of both plans, hence we bundle each plan into one so called Plan Object, which we additionally furnish with information on the plan’s preconditions, its effects and a function which returns the duration for an intended trip. In short, we are using A* routing for our implementation and calculate the required duration by accessing the max-speed fields of our simulation topology, which is based on the Open Streetmap [30] (OSM) framework.\textsuperscript{2} Regarding the preconditions, we require that the agent is in possession of a vehicle in order to have driving capability. By contrast, the walk capability requires the agent to be on foot. We define the effects of both plans to move an agent from his current location to the desired target within the period of time which is returned by the duration function of the respective Plan Object. We refer to the Plan Objects of a driver \( d \) by \( \text{Plan} \). Next, we have to provide something as an initial

\textsuperscript{2}For the walking we assumed a constant velocity of \( 4 \frac{\text{km}}{\text{h}} \) (or 2.49 \( \frac{\text{m}}{\text{s}} \)).
perception radius for the drivers. This attribute will be used by the simulation runtime to determine the current perception of the drivers. During the simulation, it is possible that the driver’s initial perception radius is altered as a result of Regional Conditions. We refer to the perception radius of a driver $d$ by $d.sight$. Given both, Plan Objects and a sight distance, the prerequisites for our drivers are defined.

5.2. Perception and Belief Revision

The phase comprises two parts. First, the currently perceived Regional Conditions are determined. In order to do so, locations and scope of elements in $Reg$ are analyzed and compared with the positions of the simulated drivers. Using (3), effects are directly applied as long as a driver is located within the scope of a Regional Condition:

$$\forall d \in D, \forall r \in Reg :$$

$$d' := \begin{cases} d' & \text{if} \forall r \in Reg, \text{dist}(d.pos, r.pos) \leq r.scope \\ d & \text{else} \end{cases}$$

where

- $\text{dist}(x,y)$ Calculates the Euclidian distance between $x$ and $y$, with $x, y \in \text{GPX}$
- $d.pos$ The current location $l$ of driver $d$, such that $l \in \text{GPX}$

After Regional Conditions have been applied, the simulation engine proceeds by updating the driver’s knowledge on Infrastructural Features. In order to do so, distances between the elements in $\mathbb{I}$ and the simulated drivers are computed and compared with the driver’s perception radius. Whenever a driver “senses” an Infrastructural Feature, it is inserted into his belief base. Also, the simulation routine verifies whether already stored Infrastructural Features are still being perceived by the agent. If that is not the case, those are removed from the agent’s belief base:

$$\forall d \in D, \forall i \in \mathbb{I} : d'.bBase = \text{update}(d.bBase, i) \quad (6)$$

where $\text{update}$ complies with:

$$\text{update} : X \times \mathbb{I} \to X, X \subseteq \mathbb{B}$$

and is defined by:

$$\text{update}(b, i) := \begin{cases} b \cup \{g_b(i)\} & \text{dist}(d.pos, i.pos) \leq d.sight \\ b \setminus \{g_b(i)\} & \text{else} \end{cases}$$

and where

- $d.bBase$ Is the belief base of driver $d$
- $g_b(x)$ A function, which generates a belief from an Infrastructural Feature, such that $g_b : \mathbb{I} \to \mathbb{B}$, where $\mathbb{B}$ constitutes the set of believes.
- $b$ Is a belief base, such that $b \subseteq \mathbb{B}$

5.3. Option Generation

In this phase, the agent determines if he is able to make use of any of the perceived Infrastructural Features by evaluating their preconditions according to (2). A failed precondition check will not change the state of the agent, but in case of a successful evaluation, the desire to make use of the Infrastructural Feature will be stored in the form of a goal within the goal base of the agent. In this goal base we differentiate between one specific superior goal, which expresses an agent’s main objective to reach a certain location and several (sub-)goals which emerge dynamically as an agent’s desire to make use of an Infrastructural Feature. The agent is compelled to his superior goal, exclusively. Other goals can be considered as alternative options in reaching his ultimate target. Whether or not an alternative option is chosen is determined by the agent’s attitudes and preferences. This decision is done within the subsequent $\text{Filter}$ phase. We formalize the $\text{Option Generation}$ process as follows:

$$\forall d \in D, b \in d.bBase :$$

$$d'.gBase := \begin{cases} d.gBase & \cup \{g_b(b)\} \setminus \{g_b(i)\} & d.gBase \setminus \{g_b(i)\}, \text{else} \end{cases} \quad (7)$$

where

- $d.gBase$ Is the goal base of driver $d$
- $g_b(x)$ Is a function, which generates a goal from a belief, such that $g_b : \mathbb{B} \to \mathbb{G}$, where $\mathbb{G}$ constitutes the set of goals.
- $b$ Is the Infrastructural Feature which is associated with the belief $b$

5.4. $\text{Filter}$

In this phase, the agent retrieves his goals from the goal base and tries to find ways to achieve them. We distinguish between two types of goals here. One goal is superior to any other goals and expresses the agent’s main objective to reach a certain location. This goal is placed within the goal base of any agent whenever he is starting his journey. The approach puts particular requirements on the simulation engine, as we are dealing with an event driven principle and a discrete simulation time. During the simulation, the simulation engine has to check if events are scheduled for the current simulation time. Whenever an event is detected, a goal is created and placed within the goal base of the driver:


\[ \forall d \in \mathbb{D} : d.gBase := d.gBase \cup \{ g_e(e) \mid e \in E, e.start = now \} \quad (8) \]

where

\[
\begin{align*}
E & \quad \text{Is the set of events.} \\
g_e(x) & \quad \text{A function, which generates a goal from an event, such that } g_e : E \rightarrow G \\
e.start & \quad \text{The scheduled start for an event } e, \text{ where } e \in E \\
now & \quad \text{The current simulation time in a discrete, event-driven traffic simulation}
\end{align*}
\]

In compliance with the single-minded principle [8], this goal will remain within the goal base of the agent until it has been achieved, or until it is no longer possible to reach the goal. Other (sub-)goals can only be generated as a result of (7), by perceiving Infrastructural Features from the topology. These goals express an agent’s desire to exploit its environment.

Now, a planning algorithm (as for instance regular backtracking or STRIPS) is used to compute available courses of action, namely strategy, which are able to satisfy the agent’s superior goal. We define a strategy as follows:

\[ s_1 \ldots s_n \mid s \in \text{Plan} \cup G, n \in \mathbb{N} \quad (9) \]

and refer to the set of strategies as Strat.

In order to compute strategies, the applied planning algorithm calculates any possible sub-goal permutation and respectively tries to accomplish the agent’s superior goal by extending this permutation with its basic capabilities. To assure consistency, the planning algorithm accesses preconditions and effects from the Infrastructural Feature, which is following (7) and (8)—directly associated with the sub-goal. Preconditions and effects of the agent’s basic capabilities are derived from the corresponding Plan Object.

As each valid course of action is temporarily retained, the result of the planning process is a set of potential strategies:

\[ \forall d \in \mathbb{D} : Strat_d := \text{genStrat}(d.gBase), Strat_d \subseteq Strat \quad (10) \]

where

\[
\begin{align*}
\text{genStrat}(x) & \quad \text{Is a function, which generates the set of consistent strategies from the current goal base of a driver, such that } \text{genStrat} : G \rightarrow X, X \subseteq Strat
\end{align*}
\]

After the set of potential strategies has been generated, the agent’s favorite strategy has to be determined. For this purpose each agent is equipped with a utility function util:

\[ Strat \rightarrow \mathbb{R} \]

which measures the quality of a proposed strategy. This measurement process represents the agent’s preference, as it is decided here by which criteria an agent selects its course of action. Using util, the strategy with the highest benefit is determined from the proposed set of options:

\[ s = \text{best}(\text{Strat}_d) \]

where best complies with:

\[ \text{best} : X \rightarrow \text{Strat}, X \subseteq \text{Strat} \]

and is defined by:

\[ \text{best}(\text{Strat}_d) := y, \quad \exists s \in \text{Strat}_d, s \neq y : \text{util}(y) \leq \text{util}(s) \quad (11) \]

Once the agent’s favorite strategy has been computed, the Filter phase will come to end and place the best strategy into the agent’s intention repository.

5.5. Actuation

In this phase, the computed strategy is executed. According to (9), a strategy can only comprise the execution of an agent’s basic capability, or an Infrastructural Feature. Both tasks are carried out by the simulation engine.

In the case of an Infrastructural Feature, the specification is provided by its effects (according to (3)) and its duration (according to (4)). Thus, in order to execute an Infrastructural Feature, the simulation engine has to apply the specified effects after the given duration. Further, as our approach is based on a discrete simulation model, the simulation engine has to exclude the driver from the simulation whilst executing the Infrastructural Feature.

By contrast, the process of executing an agent’s basic capabilities is just applying laws of motion in order to move a vehicle (or a person) from a given position A to a given position B—a principle which is more widely known as a common traffic simulation.

5.6. Optimization

Thus far, our agents are designed to constantly perceive their environment — which is not far off from reality. Yet, this principle is not feasible, if only for efficiency reasons. Moreover, it is not even necessary to compute a new strategy as long as the perception of an agent is not significantly altered, as the strategy generation is a deterministic process. We exploit this characteristic and optimize the strategy generation of our agents as follows:

3According to our definition in (11), the utility function has to be one-to-one.
s_d' := \begin{cases} 
\text{oGen, filter, } \text{d.bBase}' \setminus \text{d.bBase} \neq \emptyset \\
\text{s_d, else}
\end{cases}
(12)

where

s_d \quad \text{Is the strategy of a driver d. While } s_d \text{ describes the drivers strategy at a given time } t, 

s_d' \quad \text{describes his strategy at a given time } t+1

\text{oGen, filter} \quad \text{ Constitutes the regular strategy computation mechanism as including the option generation and the filter phase.}

An important implication of this definition is that a strategy update is not performed if a known influence has been left but only in the case when a new influence is being perceived.

6. CONCLUSION

The model was applied in three comprehensive research project evaluations. Within the Volkswagen project, we developed a parking-reservation and guidance system in cooperation with the research branch of Volkswagen AG. It was not possible to evaluate this system in reality, so we used our simulation environment in order to compare the performance of drivers that are assisted by such system to those that are not. The latter category was conceptualized by means of the BDI-based driver model, yet, to the fact that the driver model was implemented in a modular fashion, it was also possible to replace the BDI reasoning cycle with the planning capability of the assistance system. Thus, it was possible to use the same simulation model for both category of drivers. We were able to determine a significant improvement of the performance of those drivers that were in possession of an assistance system [16]. In this application, we used the Infrastructural Feature concept to conceptualize the available and bookable car parks. In the second project we developed an assistance system for the drivers of electric vehicles. The system was able to optimize the drivers' route choices and to decrease the effective emissions of the vehicles, by using information about the availability of energy from renewably energy sources and by accessing the drivers' personal calendars. Again, we used the simulation framework in order to determine the performance of those drivers that are in possession of such assistance system to those that are not. In order to do that, we conceptualized latter drivers by means of the presented simulation model. Charging stations and regular parking lots were conceptualized in compliance with the Infrastructural Feature formalism. Due to the modular architecture of the BDI model, we were again able to replace the BDI reasoning cycle with the planning capability of the assistance system and to determine the performance of those drivers that are using the assistance system as well. Based on this evaluation, and due to the simulation framework, we were able to show [18] that the assistance system is able to decrease the effective emissions of electric vehicles by roughly 50%. In the third project, we extended the above-presented assistance system for electric vehicles to account for different stakeholders, namely the driver, the infrastructure provider, the charging station operator, and the distribution system operator. The aim of this project was to design the assistance system to maximize the interests of all stakeholders in this game. In the evaluation of this project, we aimed to determine the applicability of this assistance system to different “driver profiles”, namely commuters, field workers, and delivery services. The simulation model was used to conceptualize all three driver profiles. Again, we used the Infrastructural Feature concept to conceptualize the infrastructure, which mainly involved (different types of) charging stations and parking lots. The simulation model was used for all categories of drivers, including those that were guided by the assistance system. In this evaluation, we were able to show [25] that the approach is applicable for commuters and field workers, but fails for delivery enterprises. It is most important to mention, that for all three project evaluations, the exact same simulation environment was used. This was possible due to the generic representation of those factors that have the capability to affect human strategic level driver behavior. Available frameworks implement sophisticated strategic level planning mechanisms, yet, the static way in which factors for this form of human problem solving are implemented makes it impossible to adapt these frameworks to different requirements as easy as it was possible with the approach that we presented in this paper. Wrapping up, we argue that—in order to cope with the flexible nature of human strategic level driver behavior—simulation models for strategic level driver behavior have to be implemented as flexible as possible as well.

REFERENCES


