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Game Theoretical Decision Making Approach for a Cooperative Lane Change

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Abstract: Recent advances in communications technology make it possible for vehicles to interact with each other and their environment. This allows for superior maneuvers, which open up a wide range of possibilities, which conventional vehicles without communication lack. To that end, this paper examines a decision making approach for an automated and cooperative lane change maneuver, which is based on the fundamentals of game theory. The decision making algorithm is realized with intuitive benefit functions, which are modelled similar to the semantic of human driving behavior. The used benefit functions can be classified into two sub-games: player against a single player and player against the totality of all players. By mapping four distinct driving maneuvers to their respective benefits, the problem of selecting the optimal maneuver can be solved using game theory methods. After the optimal driving maneuver has been identified, the cooperative lane change can be performed. The approach has been validated in a simulated highway scenario. Simulations have shown that a cooperative lane change does not have a significant negative effect on the traffic flow.

Keywords: automated guided vehicles, autonomous vehicles, automobile industry, cooperative lane change, decision making, game theory, traffic flow

1. INTRODUCTION

In the near future, the use of highly automated vehicles of stage four and five (according to SAE definition Society of Automotive Engineers (2016)) leads to a homogenisation of traffic behaviour. Highly automated vehicles are able to cooperate passively with other road users using their assistance systems. A passive cooperation, in the context of this paper, means the consideration of the behaviour of other road users in order to avoid the risk of an accident. In addition, advances in communication technology make it possible to use cooperative driving assistance systems. These systems go far beyond the functionalities of today's conventional assistance systems. Their use enables active cooperation, which involves a communication link between both vehicles and an exchange of (typically binary) data. This leads to cooperative driving maneuvers between road users. In our understanding, a cooperative driving maneuver is a maneuver in which two or more vehicles actively cooperates towards realizing a common driving goal. Obviously, active cooperation results in a higher degree of freedom w.r.t. possible driving maneuvers (e.g. requests can be made from one car to another).

Existing approaches for cooperative maneuvers can be found in academia and literature, for example: platooning (Sesmar-Kazerooni et al. (2017)), intersection crossing (Medina et al. (2015)) and merging (Scarinci et al. (2015)). Related work on cooperative lane change maneuvers can roughly be differentiated into rule-based (Khan et al. (2014)), benefit-based (Lin et al. (2019)) and hybrid (Sone and Kojima (2017)) approaches. Rule-based approaches are limited to discrete solution spaces. On the other hand, the advantage of rule-based approaches is the ability of tracing back the decisions that have been made. In addition, such approaches are easier to design as long as they are tailored to specific scenarios (e.g. state machines). In contrast to that, the solution space of benefit-based approaches is continuous. Approaches based on hybrid systems combine the advantages of both rule-based and benefit-based solutions.

As the proposed Game theory based Decentralized Decision Making algorithm uses both, a rule-based decision logic as well as a benefit-based calculation, it is a hybrid approach. However, neither non-linear-optimization, nor machine learning or iterative algorithms are used to solve the decision making problem. Instead, an intuitive and adaptable algorithm, mainly based on the fundamentals of game theory, has been developed. It is used to cooperatively open up a gap on an occupied overtake lane so that the automated vehicle's driving assistants can perform maneuvers to overtake the obstacle ahead. The algorithm is triggered when the adaptive cruise control (ACC) recognizes an obstacle ahead, which would force the automated vehicle to slow down. Therefore, the overtake lane is blocked; i.e. the lane change assistant cannot perform a lane-change to overtake the obstacle. In order to open up a gap on the overtake lane, every adjacent car is enumerated and the benefits for every possible (and predefined) driving maneuver, w.r.t. the adjacent car, is calculated. Next, a request for opening up a gap is sent to the adjacent cooperative car. In case the car declines the request, the next adjacent car is contacted. Finally an adjacent car opens up a gap, or the automated vehicle is forced to follow behind the obstacle using the default ACC driving assistent.

The safety relevant aspects of the algorithm are implicit in nature, due to the limited effects the algorithm has on a vehicle: The algorithm will not actively interact with any system on board of an automated vehicle, except for the speed control. The host vehicle will send a request towards another vehicle (i.e. the client) to decrease its speed, so that a gap will form. Therefore, the client vehicle's implementation must assure that the speed reduction is always safe within the parameters of maximum deceleration. Any other action taken by the host or client vehicle is a result of the existing ACC systems.

2. GAME THEORY BASICS

In game theory, the normal form is a representation of a game in a matrix, as it can be seen in Owen (1968). A game Γ with pure strategies in normal form is a 3-tuple $\Gamma = (N, \Sigma, B)$ with the following three objects:

(1) $N := \{1, 2, ..., n\}$ the set of all numbered players,
(2) $\Sigma := \Sigma_1 \times \Sigma_2 \times ... \times \Sigma_n$ the strategy space and
(3) $B : \Sigma \to \mathbb{R}^n$ the benefit functions of all players.

The set of all players is described by N. As a decision maker, the player $i \in N$, chooses a strategy $\sigma_{i,j}$ from the strategy set Σ_i. A strategy $\sigma_{i,j}$ represents an action that a player can perform. All players pursue an individual-rational goal to maximize their individual benefit function by choosing a strategy. Games with a finite number of players and strategies can be represented in a benefit-matrix, often as a bi-matrix:

		P2	
		$\sigma_{2,1}$	$\sigma_{2,2}$
P1	$\sigma_{1,1}$	$B_1(\sigma_{1,1}, \sigma_{2,1})$, $B_2(\sigma_{1,1}, \sigma_{2,1})$	$B_1(\sigma_{1,1}, \sigma_{2,2})$, $B_2(\sigma_{1,1}, \sigma_{2,2})$
	$\sigma_{1,2}$	$B_1(\sigma_{1,2}, \sigma_{2,1})$, $B_2(\sigma_{1,2}, \sigma_{2,1})$	$B_1(\sigma_{1,2}, \sigma_{2,2})$, $B_2(\sigma_{1,2}, \sigma_{2,2})$

The above shown game in normal form consists of the players $N = (1, 2)$. Player 1 (P1) and 2 (P2) can choose between the strategies $\sigma_{i,1}$ and $\sigma_{i,2}$. So the strategy space is constructed by the combination of possible strategies $\Sigma = \Sigma_1 \times \Sigma_2 = (\sigma_{1,1}, \sigma_{1,2}) \times (\sigma_{2,1}, \sigma_{2,2})$. The benefit functions $B_i(\sigma_{1,j}, \sigma_{2,j})$ represent the benefit of the players for a chosen strategy j in benefit units (BU). Players cannot choose multiple strategies in games with pure strategies. They have to decide on one strategy of their strategy set. In a first step, the strategy combinations in the nash equilibrium have to be determined. If there is a strategy combination in a game with pure strategies, so that it is not advantageous for any player to refrain from his original strategy choice, as long as the remaining player retain their strategy decision, it is a strategy combination in nash equilibrium.

Definition 1 - Nash Equilibrium
A strategy combination in nash equilibrium in a game with pure strategies is a combination of admissible strategies of all n-players that applies to any valid strategy of a player:

$$\forall i, j \in \Sigma_i :$$
$$B_i(\sigma_{1,*}, ..., \sigma_{i,*}, ..., \sigma_{n,*}) \geq B_i(\sigma_{1,j}, ..., \sigma_{i,*}, ..., \sigma_{n,*})$$

A strategy combination in nash equilibrium is a non-cooperative decision making approach. Each player individually and rationally avoids the loss of benefit. In a game with a limited number of players and strategies, several strategy combinations in nash equilibrium can occur. An additionally selection must take place because players can only choose one strategy. This selection can be made by identifying the pareto improvement. The deviation of a player from the originally chosen strategy, which at least improves the benefit of a player without reducing the benefit of another player at the same time is the pareto improvement.

Definition 2 - Pareto Optimum
A pareto optimal strategy combination in a game with pure strategies is a combination of admissible strategies of all n-players that applies to any valid strategy of a play: $\forall i, p \in \Sigma_i : B_i(\sigma_{1,p}, ..., \sigma_i, ..., \sigma_n) \geq B_i(\sigma_1, ..., \sigma_i, ..., \sigma_n)$.

A pareto improvement identifies the strategy combination with the largest possible benefit. If the players have the choice between two or more strategy combinations in the nash equilibrium, the benefit can only be improved by cooperation. The players now have to work together, to maximize their benefit.

3. CONCEPT

The sketch in Figure 1 represents the conceptual basis of the game theory approach. An automated, but not connected vehicle (green vehicle, AV) is in front of the host vehicle (orange vehicle, HV) and represents an obstacle. It could be automated or controlled by a human driver. The closer the host vehicle gets to the obstacle, the more it deviates from its desired speed. This speed reduction is required in order to avoid a collision and maintain the safety distance. In order to continue driving at the desired speed, it therefore needs to change the lane to the overtake lane. However, the overtake lane is occupied by several automated and connected vehicles (blue vehicles, ACV). The host vehicle must interact actively with the surrounding road users, to perform a lane change. This leads to a cooperative lane change maneuver with the ACV's in communication range.

3.1 Determination of Benefit

For the presented scenario, a game in normal form with two players is chosen. The game consists of the players Host and ACV. The strategy space consists of the strategy set of the host and the automated connected vehicles. As strategies for the host vehicle, the lateral maneuvers *Lane Change* (LC) and *Lane Keep* (LK) are used. Automated and connected car strategies are the longitudinal maneuvers *Open a Gap* (GAP) and *Follow Vehicle* (FV).

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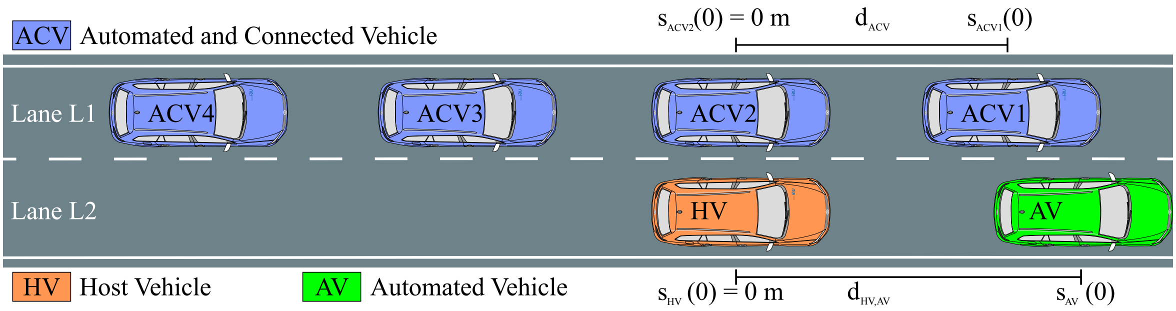

Fig. 1. Sketch of a cooperative lane change scenario

The functions B_{HF} and B_{ACV} map the benefits for both players. The following bi-matrix shows the cooperative lane change scenario as a game in normal form.

HV \ ACV	GAP	FV
LC	B_{HV}(LC,GAP), B_{ACV}(LC,GAP)	B_{HV}(LC,FV), B_{ACV}(LC,FV)
LK	B_{HV}(LK,GAP), B_{ACV}(LK,GAP)	B_{HV}(LK,FV), B_{ACV}(LK,FV)

Maneuver pairs (LC,FV) and (LK,GAP)
If strategy combination (LC, FV) is chosen, a collision between the HV and the ACV involved will occur. In combination (LK, GAP), the HV continues to follow the AV, although the involved ACV creates a gap. These two strategy combinations generate no benefit for both players. In this game no negative benefit is defined. In this scenario it is irrelevant for the decision-making process whether a benefit is zero or with a negative sign. This section defines the benefit functions for the strategy combinations (LC, GAP) and (LK, FV) for both player.

Maneuver pair (LC,GAP)
The benefits for the maneuver pair (LC, GAP) are a subgame between the HV and the gap opening candiate ACV. First, the benefit functions for the strategy combination (LC, GAP) have to be defined. For this, the distances between the host vehicle and the automated vehicle is determined using the equations of motion. At a constant velocity of the HV $v_{\mathrm{HV}} = v_{\mathrm{HV,0}}$ and considering the initial conditions for the position $s_{HV}(0) = 0\,m$ the following position function $s_{\mathrm{HV}}(t) = v_{\mathrm{HV,0}}t$ results. For the AV the position function $s_{\mathrm{AV}}(t) = v_{\mathrm{AV,0}}\,t + s_{\mathrm{AV}}(0)$ results with constant speed $v_{\mathrm{AV}} = v_{\mathrm{AV,0}}$ and the initial condition $v_{\mathrm{AV}} = v_{\mathrm{AV,0}}$. The difference between the two functions is equal to the distance between the two vehicles $d_{\mathrm{HV,AV}} = s_{\mathrm{AV}}(0) + (v_{\mathrm{AV,0}} - v_{\mathrm{HV,0}})\,t$. So far, it has been assumed that the speed of the host vehicle is constant. However, if the vehicle closes up at a higher speed up to the safety distance at the speed $v_{\mathrm{AV,0}}$, the speed is no longer constant. It must be expressed by the acceleration function of the HV $v_{\mathrm{HV}}(t) = \int_0^{\mathrm{t}} a_{\mathrm{HV}}(\tau)\mathrm{d}\tau$. If the HV is to maintain a speed-dependent safety distance $d_s(v_{\mathrm{HV}}(t))$ to the AV, then the following inequation results:

$$s_{\mathrm{AV}}(0) + \left(v_{\mathrm{AV,0}} - \int_0^{\mathrm{t}} a_{\mathrm{HV}}(\tau)\mathrm{d}\tau\right) t \geq d_{\mathrm{s}}(v_{\mathrm{HV}}(t)). \quad (1)$$

According to inequation (1), the HV must always maintain a distance of d_s or greater. The safety distance is country-specific (StVO for german rule set). The closer the HV comes to the AV, the lower the speed difference between the two vehicles and the greater the deviation from the desired speed. This leads to the conclusion that the benefit for a lane change with subsequent overtaking maneuver increases the closer the HV comes to the AVs safety distance. Finally, the benefit of the HV $B_{\mathrm{HV}}(LC, GAP)$ is represented by

$$B_{\mathrm{HV}}(LC, GAP) = \begin{cases} \max, \text{ if } d_{\mathrm{HV,AV}} \to d_s(v_{\mathrm{HV}}(t)) \\ \min, \text{ if } d_{\mathrm{HV,AV}} \to \infty. \end{cases}$$

The ACVs in Figure 1 drive with a constant speed $v_{\mathrm{ACV}} = v_{\mathrm{ACV,0}}$ in the overtaking lane L1. For example, if the ACV2 vehicle is a participant of a cooperative lane change maneuver, a braking maneuver of the vehicle must be considered. This is necessary in order to decelerate to a lower speed so that a sufficiently large gap can be created for the lane change at reduced speed. The velocity function of ACV2s reduced speed is $v_{\mathrm{ACV2,reduced}}(t_{\mathrm{ACV,Brake}}) = v_{\mathrm{ACV,0}} + a_{\mathrm{ACV,Brake}}\,t_{\mathrm{ACV,Brake}}$. Under consideration of driving comfort, the parameter $a_{\mathrm{ACV,Brake}}$ describes the maximum possible braking deceleration. In addition, the parameter $t_{\mathrm{ACV,Brake}}$ defines the maximum braking duration that a vehicle can achieve under consideration of comfort aspects. Both vehicles must maintain a safety distance of d_{s} to avoid a collision in the event of unforeseen braking manoeuvres. This safety distance corresponds to the same distance function of inequation (1). If the HV wants to change from lane L2 to overtaking lane L1, an additional safety distance to ACV2 and ACV3, as well as a distance by the required length of the lane changing vehicle (corresponding to the gap length), is required. A twofold safety distance is necessary so that the target vehicle (HV) does not fall below the safety distance to the vehicle in front (ACV1) when changing lanes and at the same time maintains the distance to the following vehicle (ACV2). Taking twice the safety distance and the length of the vehicle (l_{HV}) into account, results in the following equation for the duration:

$$t_{Gap} = \frac{l_{\mathrm{HV}} + 2\,d_s(v_{\mathrm{ACV}})}{v_{\mathrm{ACV,0}} - v_{\mathrm{ACV2,reduced}}} \quad (2)$$

According to equation (2), the less time the ACV2 takes to open the gap for the HV, the greater the benefit. If the duration of the gap opening maneuver were to be as long as the braking time of the ACV2, the benefit would reach its maximum. Conversely, this also means that the longer the ACV2 takes to open the gap, the less benefit it generates. To ensure that driving at reduced speed for the purpose of gap opening has no significant influence on driving comfort, the maximum duration must be set with $t_{\mathrm{ACV,BrakeMax}}$. If the gap-opening duration is close to a maximum opening duration $t_{\mathrm{ACV,BrakeMax}}$, the maneuver benefit leads to the minimum. Finally, the benefit of the $B_{\mathrm{ACV2}}(LC, GAP)$ is represented by

$$B_{\mathrm{ACV}}(LC, GAP) = \begin{cases} \max, \text{ if } t_{\mathrm{Gap}} \to t_{\mathrm{ACV,Brake}} \\ \min, \text{ if } t_{\mathrm{Gap}} \to t_{\mathrm{ACV,BrakeMax}}. \end{cases}$$

Maneuver pair (LK,FV)

The benefits of the maneuver pair (LK, FV) of all ACVs are abstracted to one player, because a lane change maneuver also affects the following vehicles' velocity in the overtake lane and they must be taken into account. It is a subgame between the HV and the ACVs. When performing the cooperative maneuver, the participating ACV must perform a braking maneuver to open a sufficient gap for the lane changing HV. This will disadvantage the gap opening ACV and all following vehicles, because they have to reduce their speed to maintain the safety distance to each other. In order to compensate for this disadvantage, a decentralized balanced and fair decision needs to be taken. As an intuitive solution we solved this requirement by using a random natural number for defining the benefit of the host vehicle. However, other solutions may be found which adhere to more complex requirements (e.g. decisions based on the vehicle's state or surroundings). This random number represents the benefit between the possible minimum and maximum values. The introduction of the politeness factor has the consequence that not every benefit assessment necessarily leads to a request for a lane change. So the benefit of the HV $B_{\mathrm{HV}}(LK, FV)$ is represented by a Random Integer Number.

Nagel and Schreckenberg (1992) describes the dynamics of the traffic flow as a cellular automaton. Whilst this model has been developed in the late 90s, it is still considered a relevant tool for traffic simulation and used in active research (see a, b, c). A cellular automaton is used to describe spatially discrete dynamic systems. Therefore the space is discretized in cells. A finite number of states is assigned to each cell. The time-discrete state changes of each cell follows defined development rules. So, the development of the cells depends on their conditions and the condition of the cells in the immediate neighborhood. In the Nagel-Schreckenberg model, roads are partitioned into 7.5 m long route sections. This length of the route sections is the sum of the average car length of 5 m and the minimum safety distance of 2.5 m in a traffic jam. The route sections correspond to the cells of a cellular automaton, the road represents the cellular space. A route section can only adopt the states free or occupied. Is the state of a route section occupied, a car is in this segment. Otherwise it is free. All cars assign a velocity number from 0 VU to 7 VU in velocity units (VU). The velocity units represent the velocity range from 0 km/h to 189 km/h. A velocity unit is equivalent to 27 km/h or 7.5 m/s. So, a velocity unit represents a multiple of a road section. In each simulation step, also called rounds, the speed and the position on the track are calculated for each vehicle. The calculation of the speed shall be based on the following three rules:

(1) **Accelerate** If a vehicle has not reached the maximum speed of 7 VU, the speed v of the vehicle is increased by one unit.
(2) **Safety** If the vehicle drives on the road with a higher speed than sections are free ahead, the speed v is reduced to the number of free cells in front of the vehicle.
(3) **Junk** With a certain probability p, the speed v of the vehicle decreases by one unit.

The acceleration rule describes the driver's preference to travel at maximum speed. In the safety rule, the safety distance is taken into account in order to avoid rear-end collisions. With the junk rule, Nagel and Schreckenberg take into account the imperfection of drivers who with a certain probability react p sluggishly, brake strongly or reduce speed slightly for other reasons while driving. The position of the vehicles depends on the speed v. At the end of each simulation step, all vehicles are shifted the number of fields in positive direction as they are assigned speed values. These rules describe the state development of the cellular automaton. In order to determine the benefit of the ACV $B_{\mathrm{ACV}}(LK, FV)$ for the refusal of the lane change maneuver, the scenario is simulated using the Nagel-Schreckenberg model. If the execution of the cooperative maneuver leads to a traffic jam with at least three involved vehicles, the benefit of refusing is maximum. Simulations have shown that a phantom jam can be caused by the participation of at least three vehicles. Conversely, this means that if there is no congestion predicted, the benefit for refusal is minimal.

3.2 Decision Logic

The decision-making process is performed by the host vehicle. It must provide a unique solution, so that both players can decide to carry out a coordinated maneuver. A unique solution must consist of a maneuver pair, one for each player. First, the system detects all ACV's within a radius of 500 m. This range describes a distance at which sufficient potential candidates for a cooperative lane change can be identified at maximum speed. State of the art systems are not yet able to detect vehicles in this range. In the near future a range of 500 m can be achieved with vehicle to vehicle (V2V) communication. The host vehicle has information about the states of position and speed, as well as lane information of all detected vehicles. In the next step, the system generates a list of all detected ACV's behind the host vehicle and in the overtaking lane. This list is sorted by ascending distance to the host vehicle. It then determines which vehicles are at a sufficient distance to open the gap. With the following algorithm candidates can be chosen.

Algorithm 1 Candidate Search

```
calculate lane position after acceleration
for vehicle in vehicle_list do
    predict lane position after gap opening
    if compare positions then
        add to candidate list
    end if
end for
```

The candidate search starts with the calculation of the travelled path to accelerate the host vehicle up to final speed. To get the position of the host vehicle after accelerating the travelled path is added to the starting position.

For every vehicle in the sorted list the position after the gap opening is predicted. Then the position of the host vehicle is compared to current vehicle in the loop. If the difference of the positions is larger than the safety distance the ACV is added to the list of candidates. Once the candidates have been identified, the decision-making process begins. To do this, the first ACV in the list becomes the target vehicle. At the first step of the decision-making the benefits for both players will be determined. Then the existence check of the strategy combinations in nash equilibrium takes place. The strategy combinations $(ALCA, GAP)$ and (ACC, ACC) are always combinations in nash equilibrium if the conditions $B_{\mathrm{HV}}(\sigma_{\mathrm{HV,i}}, \sigma_{\mathrm{ACV,j}}) > 0\,\mathrm{BU}$ and $B_{\mathrm{ACV}}(\sigma_{\mathrm{HV,i}}, \sigma_{\mathrm{ACV,j}}) > 0\,\mathrm{BU}$ for all $i = j$ are true. According to the Game Theory Basics it is not advantageous for any player to deviate from the strategy combinations in nash equilibrium.

However, the existence of two strategy combinations in nash equilibrium does not indicate which maneuver has to be performed. Therefore, in a second step, an equilibrium selection using pareto improvement takes place. If the conditions are met, three relevant cases can be differentiated:

First Case: Permission
If the benefits $B_{\mathrm{HV}}(LC, GAP)$ and $B_{\mathrm{ACV}}(LC, GAP)$ are greather than $B_{\mathrm{HV}}(LK, FV)$ and $B_{\mathrm{ACV}}(LK, FV)$, so the combinations (LC, GAP) and (LK, FV) are strategy combinations in nash equilibrium. In addition, the combination (LC, GAP) is also the pareto improvement. Consequently, the equilibrium selection leads to a unique solution. Because there exists a unique solution, the host vehicle sends a request via vehicle to vehicle communication to the target ACV. With this request, the target ACV is asked for permission to carry out the lane change. In a final instance, the target vehicle can refuse the lane change maneuver when not giving the permission. If the target ACV refuses the maneuver, the next ACV in the list is set as target ACV and the decision-making process is repeated. When the target ACV agrees to the maneuver, the cooperative lane change will be carried out. For this, the ACV brakes with a deceleration of $a_{\mathrm{ACV,Brake}}$ over a period of $t_{\mathrm{ACV,Brake}}$. It then maintains the reduced speed $v_{\mathrm{ACV,reduced}}$ until a sufficiently large gap is created. If a gap with sufficient length has been created, the host vehicle switches to the overtake lane. After the lane change, the host vehicle is at the respective safety distances to the target ACV and the ACV in front.

Second Case: Refusal
If the benefits $B_{\mathrm{HV}}(LC, GAP)$ and $B_{\mathrm{ACV}}(LC, GAP)$ are equal to the uses $B_{\mathrm{HV}}(LK, FV)$ and $B_{\mathrm{ACV}}(LK, FV)$, so the combinations (LC, GAP) and (LK, FV) are strategy combinations in nash equilibrium. However, there are also two pareto improvements (LC, GAP) and (LK, FV). So, the equilibrium selection via pareto improvement does not lead to a unique solution. In this case there will be no request from the host vehicle for a cooperative lane change maneuver. The next ACV in the list will be set as target and the decision-making process is repeated.

Third Case: Refusal
If the benefits $B_{\mathrm{HV}}(LC, GAP)$ and $B_{\mathrm{ACV}}(LC, GAP)$ are smaller then the uses $B_{\mathrm{HV}}(LK, FV)$ and $B_{\mathrm{ACV}}(LK, FV)$, so the combination (LK, FV) is a strategy combination in nash equilibrium. Furthermore, the combination (LK, FV) is the pareto improvement. Unlike the second case, the equilibrium selection leads to a unique solution. In this case there will be no request from the host vehicle for a cooperative lane change maneuver. The next ACV in the list will be set as target and the decision-making process is repeated.

4. PROOF OF CONCEPT

Figure 1 is used as a sketch for a possible future scenario on a highway section. Automated and connected vehicles (ACV, HV) represent the majority of road users. On the right lane L2 is an obstacle vehicle (AV) that prevents a high-priority vehicle (HV) from maintaining its desired speed. Examples for a high-priority vehicle could be a fire truck, police car or a ambulance vehicle. The scenario is represented in the micro traffic flow simulation software SUMO. For this purpose, simulations with and without cooperation are carried out. Finally, the simulation results are compared with regard to the differences in average speeds and distances covered.

4.1 Scenario

At the beginning of the highway scenario, the HV is on the right lane L2. It runs at a speed of $130\,\mathrm{km/h}$, which is also its desired speed. The AV drives on the right lane L2 at a speed of $80\,\mathrm{km/h}$. On the overtake lane L1, the ACV's drive at a speed of $130\,\mathrm{km/h}$. To avoid a collision with vehicle AV, the HV must adjust its speed. Since the fast lane is occupied by the ACV's, the HV cannot change lanes on its own. In case cooperative logic is inactive, the HV will therefore follow the AV using the conventional ACC. When the cooperative logic is active, it now runs the Candidate Search algorithm. If a potential candidate is found, the benefits are calculated and the decision logic executed. When the decision logic comes to the conclusion that the execution of the cooperative maneuver does not represent a significant negative impact (see below) on the traffic flow, the cooperative lane change is performed. A two-lane motorway section was used for the simulation. The SUMO simulation parameters are configured as follows: maximum acceleration ($5\,\mathrm{m/s^2}$) and braking deceleration ($4\,\mathrm{m/s^2}$). For the maximum duration of the braking process, which is part of the algorithm, 2 seconds were set. Thus the maximum possible speed difference is $8\,\mathrm{m/s}$. The duration of the gap opening maneuver with reduced speed t_{Gap} for reaching the maximum benefit lies in a time period of 0 seconds and 20 seconds. In proof of concept the driving speed is constant, but will be dynamic in a real world scenario. However, this does not impact the algorithm, as it simply modifies t_{Gap}.

4.2 Result

Table 1 shows an overview of the differences in average speed and travelled distance of every participating vehicle over a simulation period of 21 seconds. For every vehicle two measurements have been taken: One with enabled cooperation logic and one without. As described above, the vehicle did not change the lane in the latter case.

Table 1. Speed and distance difference

Vehicle	Speed diff. in km/h	Distance diff. in m
HV	+29.41	+171.56
ACV1	-20.57	-119.99
ACV2	-10.41	-60.73
ACV3	-3.15	-18.38
ACV4	0.0	0.0
Σ	**-4.72**	**-27.53**

In cooperative mode the host vehicle drives at an average speed of 92.99 km/h. With non-cooperative driving it reaches 63.58 km/h. This corresponds to a speed difference of 29.41 km/h. Thus the host vehicle covers a further distance of 171.56 m in the same time period with cooperative driving. This result shows an improvement for the individual highway vehicle in both average traveling speed as well as distance. However, the higher average speed of the host vehicle has an negative effect on the average speeds and distances covered by the ACVs. On the average, each participating vehicle (including HV) travels at a lower speed of 0.94 km/h and consequently a shorter distance of 5.51 m in a period of 21 s. In addition, it can be seen that both the speed and distance differences of vehicle ACV4 are zero, which implies that the cooperative maneuver execution of the HV has no effect on the traffic flow of AC4. It is the result of the execution constraint, which ensures that there is no significant negative impact on the traffic flow. This is achieved by using the Nagel-Schreckenberg model (for deciding whether the lane change is executed or not), which ensures that vehicles behind ACV3 must not brake, as this would case a traffic jam. The additional space, which has been occupied by the HV on the overtake lane, has been distributed between ACV1 to ACV3. As described above, these three ACVs needed to brake for making the lane change of the HV possible.

5. CONCLUSION AND OUTLOOK

As could be seen in the results section, cooperative lane change maneuver will increase the HV's average driving speed by 29.41 km/h, but in turn decrease the speed for at least one ACV on the overtake lane (i.e. the AV which opens up the gap for the HV) by 4.72 km/h. However, in every right-hand traffic environment, the right lane will be loaded with more vehicles, than the overtake lane. In addition, a vehicle usually switches from the overtake (left) lane back to the cruising (right) lane once the overtake maneuver has been completed. Therefore, a vehicle will spend more time on the cruising lane, than on the overtake lane. Due to this fact, a temporary reduction in traveling speed on the overtake lane has less effect, than the speed increase due to the overtake maneuver. While every vehicle may therefore gain speed during the overtake maneuver (in the host vehicle role), and lose speed during the gap opening (in the ACV role) it will none the less experience an overall improvement w.r.t. the traveling speed.

The presented assistance system can extend existing highly automated driving systems by a cooperation function for lane change maneuvers, without needed to be redesigned or fundamentally modified. Because it only has access to the vehicle's communication interface, the highly automated driving system cannot be transferred into a critical state. Without the use of non-linear optimization, iterative algorithms or methods of machine learning, an intuitive algorithm with a short run-time is presented. Using physical modelling, intuitive benefits for a lane change maneuver are determined. On this basis, game theory is used to make a fair decision for all participants. The game is classified in vehicle vs. single vehicle and vehicle vs. all vehicle subgames to also consider the negative impacts for the following cars. As the simulation shows, the system manages the lane change without a considerable negative influence on the traffic flow and it remains almost constant.

Although it is a fair and an intuitive algorithm, it has the following limitations: the traffic flow is not optimized. For optimizing the effects on the traffic flow, three parameters need to be determined. Firstly, the maximum speed difference between HV and AV on the overtake lane. Secondly the distance between the AVs on the overtake lane (as the opened gap needs to be large enough for the HV plus safety distance). And finally the speed difference between HV and the preceding vehicle in front (how much reduction in speed is acceptable for the HV, before it will use the cooperative logic to overtake the vehicle in front?). In future work the algorithm will be evaluated in a vehicle on a test track. While the algorithm is limited by its decentralized nature, multiple traffic optimizations are possible by modifying the benefit functions (e.g. do not change lane before traffic lights).

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