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Cooperation of Cars and Formation of Cooperative Groups

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***Abstract*— Cooperation of cars capable to communicate bears a high potential with respect to safety in critical situations. Following a top-down design, cars form *cooperative groups*, exchange information available to them and establish a *common relevant picture* upon which critical situations are detected, optimal decisions for the groups are derived and are distributed in form of individual action sequences. This paper focuses on the formation of *cooperative groups*. To this end, a graph-based spatiotemporal distance measure is developed, using the concept of virtual meeting points within the road infrastructure. The distance measure is analyzed and it serves to define *cooperative groups* of *cognitive automobiles*.**

I. Introduction

During the past two decades, a wide variety of driver assistance systems has been studied, e. g. anti-lock braking system, adaptive cruise control, parking assistance, emergency braking, intersection assistance, and incident warning [1]. The goals of those individual systems are to increase either comfort or safety, and they have contributed to a significant reduction of deaths on the roads [2]. However, most of these approaches focus on specific scenarios and do not pursue a generic strategy. Especially, the potential of coordinated actions taken by multiple vehicles is not exploited in existing systems.

In our research, we consider the scenario of multiple vehicles equipped with intelligent sensor data processing (e. g. video-based object detection and lane tracking) and cognitive behavior decision modules. It is assumed that the vehicles are capable of wireless communication, but that no infrastructure to vehicle communication is available. Legal issues are not considered at this stage of research.

We propose a top-down strategy for obtaining optimal cooperative decisions. In the first step of this approach, vehicles are partitioned into cooperative groups. The subsequent steps of situation recognition and behavior decision are restricted to vehicles within one group, which makes the computational efforts feasible. Our general concept is described in more detail in Section III, after a short review of related work in Section II.

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This paper is mainly concerned with the question of how to establish cooperative groups in a self-organized way. We assume that no superordinated technical infrastructure is available that coordinates car groups. Therefore, local mechanisms are to be developed which allow autonomous formation of cooperative groups based on certain criteria. For this purpose a graph-based distance measure between cars is proposed in Section IV. It quantifies the possibility whether two cars could meet on the traffic infrastructure within a certain time horizon. Using the concept of the earliest reachable meeting point, spatial and temporal aspects of car distance on the traffic infrastructure are covered. The actual formation of cooperative groups is driven by an objective function which is computed by cars and groups in order to evaluate the current group constellation and alternative partitions in the next time step. The objective function is based on the distance measure and accounts in different additive components for intra-group distances, compression/expansion rate, group size, temporal steadiness etc., as will be described in detail in Section V.

With simulation results it is shown in Section VI, that this new approach leads to an automated dynamic formation of cooperative groups which is very much in accordance with the expectation of a human observer having a bird's eye view on the scenery. Finally, Section VII contains some concluding remarks.

II. Related Work

Related projects such as 'CarTALK 2000', 'PReVENT' and 'Network on Wheels' also consider car to car communication and its application to incident warning [3]–[5]. However, the work focuses on technical aspects of the ad hoc communication, while cooperative behavior is studied only marginally.

In [6], cooperation of autonomous vehicles is studied from a scheduling perspective. However, the authors assume a controlled environment within a factory automation scenario and rely on a supporting infrastructure. The work focuses on an optimal intersection throughput and does not consider emergency situations comparable to traffic accidents.

The use of communication to enhance perception is described in [7]. The article [8] presents some ideas on cooperative vehicles, mainly concerning the improvement of traffic flow. In this context, there is some work on platoons or vehicle convoys, but the proposed formation algorithms are restricted to highways without intersections [9], [10].

Cooperative behavior of autonomous agents has been studied in other contexts, e. g. the RoboCup competitions [11]–[13]. In robot soccer, many heuristics are used which

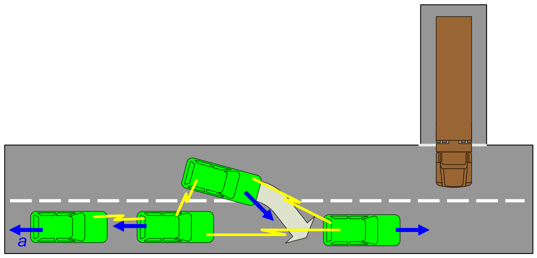


Fig. 1. This example shows a dangerous situation generated by an obstacle entering a road where a car is just overtaking a group of other cars. A coordinated action of all involved cars could avoid a possible accident. From the individual perspectives of the drivers, it is difficult to overview the complete scenario to find the best group strategy and to coordinate all necessary actions within the remaining time. To exploit the safety potential of such situations, automated assistance systems are necessary capable to analyze the complete constellation and to coordinate the actions of the individual cars automatically.

have no guaranteed success. These methods may not be applied in the field of intelligent vehicles due to safety considerations.

There is some work on groups of vehicles, but it mainly focuses on establishing ad hoc communication networks. In these publications, e. g. [14]–[16], groups only are an auxiliary means for structuring the communication network, without having a semantic concerning cooperative behavior.

The distance measure presented in this contribution has some similarities with concepts from hybrid systems reachability analysis [17], [18]. However, our method is more frugal in order to enable a real-time implementation. It is important to point out that the distance measure described in Section IV does not perform a state space search.

III. Cooperation of Vehicles

Drivers of cars basically act as independent individuals pursuing their own ambitions and destinations. Obeying the traffic rules, the drivers interact with other traffic participants in order to safely manage their trips. A sequence of individual decisions has to be made by each driver along his journey. In riskless situations most of the drivers prefer to be one's own master. But in dangerous situations automated help is appreciated [19]. Car industries offer in the meantime several intelligent assistance functions, like brake assist systems that automatically decelerate the vehicle if a collision is predicted [20]. Up to now, those automated safety systems enhance the individual capabilities of cars and drivers in order to react adequately especially in case of emergency.

In contrast, the potential of coordinated actions of groups of cars in dangerous situations is still at the very beginning of its exploitation (see Fig. 1).

From a game theory point of view there is a gap between the performance of selfishly operating agents (cars with drivers) and the optimal performance of a system where all agents are coordinated from a bird's eye view. The difference in performance due to the lack of cooperation is called the *price of anarchy* [21], [22]. Since in complex scenarios the price of anarchy can be large, it bears a high potential for improving performance (safety in our case) by local, self-organized cooperation, even if the absolute optimum is not achieved by a such an approach.

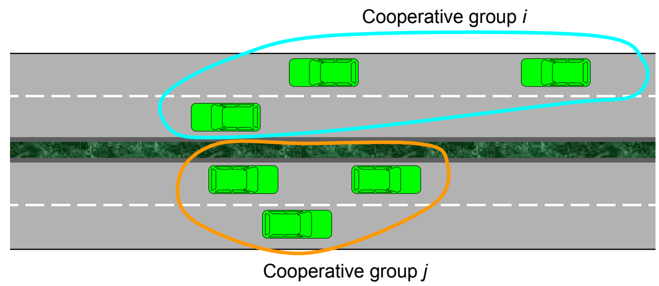


Fig. 2. Even though all six cars in this highway example are close enough to communicate, because of the barrier between the lanes only the two indicated clusters constitute suitable groups from a cooperation point of view.

To exploit the safety potential of the cooperation of cars in dangerous situations, the following philosophy is pursued. Cars capable to communicate contact cars within their communication range. Since not all of those cars can effectively cooperate – e. g. cars that are physically separated by a barrier – in a second step *cooperative groups* are established as subsets of communicating groups (see Fig. 2).

The members of a cooperative group exchange information at their disposal, i. e. sensor-based information of their surroundings, in order to establish a *common relevant picture* (CRP) of their mutual situation. The CRP contains all information that is necessary to understand and to assess the situation of the cooperative group, i. e. position and velocity data of all group members, of other traffic participants and obstacles, information about intentions and about current physical capabilities. Additionally, concerning all facts within the CRP, pertaining uncertainties are represented as well. The CRP establishes a kind of local bird's eye view on the scenario.

Based on a formal representation of the CRP, inferential processes watch for dangerous situations. If such a situation is detected, an optimal decision for the behaviour of the complete cooperative group is derived. Dangerous means here, that with high probability an accident would happen, if control was left to the human drivers. The optimal decision is then divided into individual action sequences which are distributed to the cars, where they are executed automatically by the individual control systems. As soon as the cooperative group is in a safe situation again, control is returned to the drivers.

The optimal cooperative driving maneuver will be selected based on a hierarchical set of goal functions. Among these, safety has the highest priority. Whenever possible, accidents must be avoided. If an accident is unavoidable, the risk of injuries has to be minimized. The second priority goal is the obedience to traffic regulations. A car may violate the traffic regulations if this is the only possibility to prevent an accident. In all other situations, the vehicles have to act in compliance with traffic regulations. Further suitable criteria

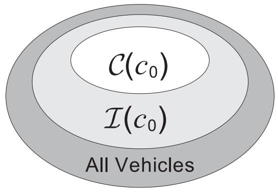


Fig. 3. Sets of cars at different levels of cooperation with car c_0.

are travelling time, passenger comfort (e. g. avoidance of abrupt decelerations), and energy consumption.

IV. Distance Measure for Road Vehicles

A. Two Levels of Cooperation

In general, a given car will not be able to cooperate reasonably with all cars within its wireless communication range. We differentiate between two different levels of cooperation: exchange of information and cooperative behavior. The latter is only possible when the vehicles under consideration are on the same road or on roads intersecting within a small neighborhood. Vehicles driving on nearby but physically seperated roads are not able to perform coordinated actions because they cannot reach each other within an adequate amount of time. However, they may gain from exchanging information with one another.

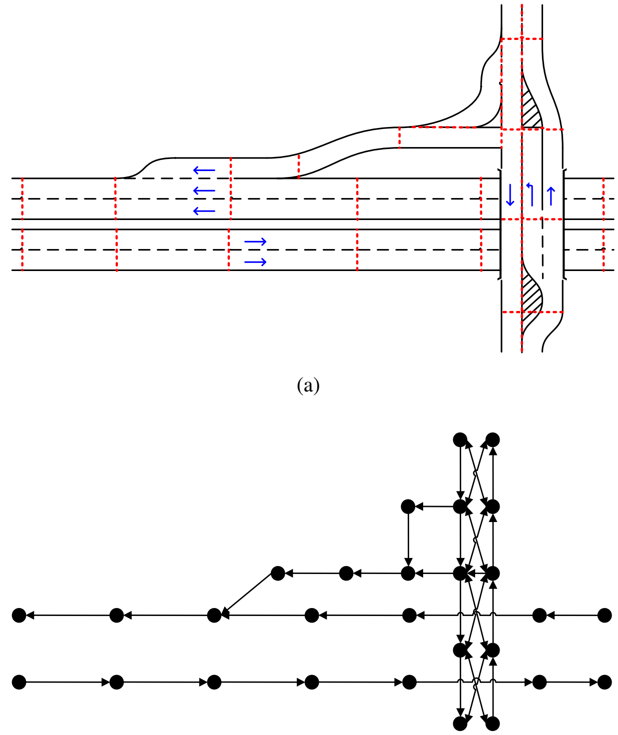
For example, cars driving in opposite directions on a highway with physically seperated directions of traffic can warn each other of incidents or congestions ahead, while they have no possibility to take joint actions (cf. Fig. 2).

The two kinds of cooperation can be formalized by set-theoretic concepts. Let c be a given vehicle. Then we define $\mathcal{C}(c)$ to be the set of vehicles which may take coordinated actions, and $\mathcal{I}(c)$ as the set of vehicles which may exchange information with c. Since vehicles have to communicate in order to coordinate their actions, $\mathcal{C}(c)$ is a subset of $\mathcal{I}(c)$, as depicted in Fig. 3.

In the remainder of this section, we address the question of determining the set $\mathcal{C}(c)$. To this end, we formally develop and analyze a distance measure.

B. Graph-Based Distance Measure

As pointed out in the previous subsection, the road topology plays a major role in deciding whether a vehicle is contained in the set $\mathcal{C}(c)$. We propose a discretization of the road area that can be formalized as a graph $\mathcal{R} = (\mathcal{V}, \mathcal{E}, w)$. Therein, the vertices in $\mathcal{V}$ represent parts of roads. Together, they form a partition of the road network. The set $\mathcal{E} \subset \mathcal{V} \times \mathcal{V}$ contains directed edges between vertices that are connected in the road topology. The weight function $w : \mathcal{E} \to \mathbb{R}$ assigns to each edge $e = (v_1, v_2)$ the minimal time a vehicle requires to drive from v_1 to v_2. It is computed taking into account speed limits and physical maximum speeds, determined by the vehicles' driving abilities as well as by the road curvature and gradient. The reason for choosing the *minimal* time is that it yields an optimistic criterion which may overestimate the set of cooperating vehicles. An underestimation would



(a)

(b)

Fig. 4. (a) Example of a road network, in which the partition into disjoint vertices is indicated with dotted lines. (b) The graph $\mathcal{R}$ corresponding to (a).

cause a loss of safety since potentially conflicting vehicles might be overlooked.

Given a road topology, the corresponding graph has distinct vertices for each direction of traffic. Besides the edges connecting the vertices within one direction of traffic, additional edges are required to model possible lane change and turn off maneuvers (see Fig. 4 for an example).

A vehicle c is assigned to the vertex $v(c)$ containing its center of gravity. Therefore, we can define the distance between the vehicles c_1 and c_2 via the distance between the corresponding vertices:

$$d(c_1, c_2) := d(v(c_1), v(c_2))\,. \qquad (1)$$

Let $p_{\mathcal{R}}(v_1, v_2)$ be the length of the shortest path from v_1 to v_2 in $\mathcal{R}$, or ∞ if no such path exists. As can be shown by examples such as the one in Fig. 5, $p_{\mathcal{R}}$ itself is not a suitable measure for determining cooperative groups. The reason is that $p_{\mathcal{R}}$ is based only on the current positions of the vehicles and does not take into account possible future motions: vehicles may have a long connecting path, while they can meet at a much shorter distance. The development of a more suitable distance measure can be illustrated in Fig. 6. Consider a subgraph $\mathcal{S} = (\mathcal{V}_{\mathcal{S}}, \mathcal{E}_{\mathcal{S}})$ of the road network $\mathcal{R}$. The set $R(v_0)$ of vertices reachable from $v_0 \in \mathcal{V}_{\mathcal{S}}$ is given by

$$R(v_0) = \{v \in \mathcal{V}_{\mathcal{S}} :\ p_{\mathcal{S}}(v_0, v) < \infty\}\,. \qquad (2)$$

The location where two vehicles c_1, c_2 can meet must be contained in the intersection of the sets of vertices reachable

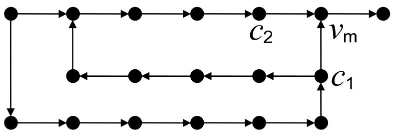
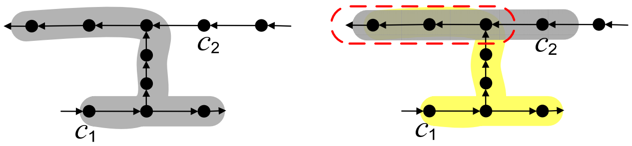


Fig. 5. Example of a situation in which the path length $p_{\mathcal{R}}$ is not a suitable distance. Assuming unit edge weights, we have $p_{\mathcal{R}}(c_1, c_2) = 8$, while both cars will meet each other at v_{m} in the next time step. Accordingly, $d(c_1, c_2) = 1$.



(a) (b)

Fig. 6. (a) A subgraph of the road network. The set $R(c_1)$ of vertices reachable from car c_1 is highlighted. (b) The same subgraph with the vertices $R(c_2)$ reachable from car c_2 indicated. The intersection of the two sets of vertices is the set $M(c_1, c_2)$ of potential meeting points.

from the current locations v_1, v_2 of the vehicles. This intersection,

$$M(c_1, c_2) := M(v_1, v_2) := R(v_1) \cap R(v_2)\,, \tag{3}$$

is called the set of potential meeting points of the vehicles c_1 and c_2.

A suitable distance measure is the minimal time required until both cars reach a common meeting point in $M(c_1, c_2)$.

Now, the distance measure d can be formally defined using the concept of virtual meeting points. The distance from two vertices v_1, v_2 to a meeting point v_{m} is the larger value of the path lengths to v_{m} in $\mathcal{S}$: $\max\{p_{\mathcal{S}}(v_1, v_{\mathrm{m}}), p_{\mathcal{S}}(v_2, v_{\mathrm{m}})\}$. Finally, the distance between two vertices is obtained by minimizing this quantity over the possible meeting points:

$$d(v_1, v_2) := \min_{v_{\mathrm{m}} \in M(v_1, v_2)} \max\{p_{\mathcal{S}}(v_1, v_{\mathrm{m}}), p_{\mathcal{S}}(v_2, v_{\mathrm{m}})\} \tag{4}$$

C. Determining the Sphere of Cooperation

A sphere of cooperation with radius r for a given vehicle c_0 is defined as

$$\mathcal{C}_r(c_0) := \{c \mid d(c, c_0) \le r\}\,. \tag{5}$$

It is not suitable for vehicle c_0 to form a cooperative group with cars outside $\mathcal{C}_{r_0}(c_0)$ when r_0 is an appropriately chosen threshold radius. This assumption can be used to reduce the computational costs considerably, as will be shown in Subsection IV-E.

This concept also enables the construction of the subgraph $\mathcal{S} = (\mathcal{V}_{\mathcal{S}}, \mathcal{E}_{\mathcal{S}})$ mentioned in the previous subsection. Let

$$\mathcal{V}(c) := \mathcal{V}(v(c)) := \{v \in \mathcal{V} \mid d(v(c), v) < r_0\}\,, \tag{6}$$

then the set of vertices of the subgraph is given by

$$\mathcal{V}_{\mathcal{S}} := \bigcup_{c \in \{c_1, \ldots, c_n\}} \mathcal{V}(c)\,, \tag{7}$$

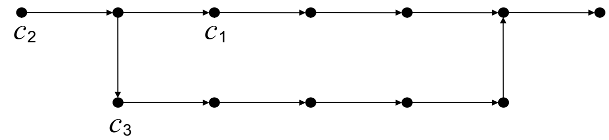


Fig. 7. This counter-example shows that the distance measure does not fulfil the triangle inequality: assuming unit edge weights, $d(c_1, c_2) = 2$, $d(c_2, c_3) = 2$, and $d(c_1, c_3) = 5$, while the triangle inequality would require $d(c_1, c_3) \le d(c_1, c_2) + d(c_2, c_3)$.

when considering the n vehicles $\{c_1, c_2, \ldots, c_n\}$. The edges of the subgraph are given by

$$\mathcal{E}_{\mathcal{S}} := \{e = (v_1, v_2) \in \mathcal{E} \mid v_1, v_2 \in \mathcal{V}_{\mathcal{S}}\}\,. \tag{8}$$

D. Properties of the Distance Measure

In this subsection, we will examine whether the distance measure fulfils the mathematical axioms of a metric [23].

1) Positiveness: The distance measure is positive definite: $d(c_1, c_2) \ge 0$. It is zero if $c_1 = c_2$. The converse, $d(c_1, c_2) = 0 \Rightarrow c_1 = c_2$, holds if the discretization of the road network is fine enough that at most one vehicle fits in a vertex.

2) Symmetry: The distance measure is symmetric: $d(c_1, c_2) = d(c_2, c_1)$. This follows immediately from the defining equation (4).

3) Triangle Inequality: The triangle inequality does not hold. This is shown by the counter-example depicted in Fig. 7.

Consequently, d is not a metric. However, this property of the distance measure does make sense intuitively: the triangle inequality would require cars c_1 and c_3 in Fig. 7 to have a distance ≤ 4, although they can reach their nearest meeting point not before 5 units of time have passed.

E. Computational Complexity

At first glance, one might suspect that the minimization over v_{m} in (4) would cause huge computational costs. However, the distance measure can be calculated much more efficiently than by computing $p_{\mathcal{S}}(v_1, v_{\mathrm{m}})$ and $p_{\mathcal{S}}(v_2, v_{\mathrm{m}})$ for every $v_{\mathrm{m}} \in \mathcal{V}$.

Considering two vertices v_1 and v_2, our implementation performs simultaneous uniform cost searches starting at v_1 and v_2. Similar to Dijkstra's shortest path algorithm, the vertex v_0 having minimal path length from one of the starting points is expanded in every step [24], [25]. The nearest meeting point v_{m} is reached when the two search trees meet for the first time. Uniform cost search has a computational complexity of $\mathcal{O}(|\mathcal{E}| log |\mathcal{V}|)$, where the logarithmic factor is due to the priority queue of nearest vertices [25]. Here and further on, we assume $|\mathcal{V}| \le |\mathcal{E}|$ for simplification, which is reasonable as every vertex must have at least one outgoing edge in a real road network.

Another reasonable assumption is an upper bound b on the branching degree. A vehicle situated at a vertex v may drive straight forward on its lane, change to one of at most two neighboring lanes, turn left or right, so that

$b = 5$ seems justified. Further, we assume $w(e) > \varepsilon$ for all $e \in \mathcal{E}$. Together with the observation that the algorithm can be terminated when the search frontier exceeds the radius r of the cooperation sphere, this leads to another upper bound on the computational complexity (cf. [24]): $\mathcal{O}(b^{1+\frac{r}{2\varepsilon}} log(b^{1+\frac{r}{2\varepsilon}}))$. Note that this bound is independent of the graph size.

It is also possible to compute the distance measure $d(v(c_i), v(c_j))$ of all pairs of the n considered vehicles simultaneously ($1 \leq i, j \leq n$). The algorithm is modified such that all vertices corresponding to vehicles constitute starting points of uniform cost searches. This implementation has a computational complexity of $\mathcal{O}(n|\mathcal{E}|log(n|\mathcal{V}|))$ or $\mathcal{O}(nb^{1+\frac{r}{2\varepsilon}} log(nb^{1+\frac{r}{2\varepsilon}}))$.

V. Formation of Cooperative Groups

In this section, we describe a distributed algorithm for the partition of vehicles into disjoint cooperative groups.

Disjoint cooperative groups can only achieve an approximation to the optimal cooperative behavior, but this already is a considerable improvement compared to selfish behavior. In the future, we will investigate whether overlapping groups and inter-group communication yield further benefits.

A. Objective Function for Cooperative Groups

The distance measure is the key component needed for establishing an objective function which attains its minimum at the optimal group assignment. Let $\mathcal{G} = \{c_1, \ldots, c_m\}$ be a cooperative group. Then we define the objective function $s(\mathcal{G})$ to be a weighted sum of several terms,

$$s(\mathcal{G}) := \lambda_{\mathrm{D}} s_{\mathrm{D}}(\mathcal{G}) + \lambda_{\mathrm{V}} s_{\mathrm{V}}(\mathcal{G}) + \lambda_{\mathrm{S}} s_{\mathrm{S}}(\mathcal{G}) + \lambda_{\mathrm{T}} s_{\mathrm{T}}(\mathcal{G}) . \quad (9)$$

The individual terms take into account the different desired properties of cooperative groups, as will be described in the remainder of this subsection. The relative weights of the terms can be adjusted by the parameters $\lambda_i > 0$.

The first summand $s_{\mathrm{D}}(\mathcal{G})$ directly incorporates the distance d between the vehicles of the group. It can be defined as

$$s_{\mathrm{D}}(\mathcal{G}) := \begin{cases} 0 & \text{if } m \leq 1 \\ \frac{1}{m(m-1)} \sum_{i=1}^{m} \sum_{j=i+1}^{m} d(c_i, c_j) & \text{if } m > 1 . \end{cases}$$

The sum is divided by the number of its summands in order to seperate the concerns of the spatial extension and the number of members of the group.

The second term $s_{\mathrm{V}}(\mathcal{G})$ represents the relative velocity of the vehicles belonging to the group $\mathcal{G}$, and thus the expansion rate or compression rate of the group, respectively. If two cars approach each other, it is likely that there will be a need for cooperative actions. In contrast, cars going away from each other will rarely be able to take suitable cooperative actions. So a negative relative velocity should encourage the formation of a group, which is accomplished by decreasing its objective function,

$$s_{\mathrm{V}}(\mathcal{G}) := \begin{cases} 0 & \text{if } m \leq 1 \\ \frac{1}{m(m-1)} \sum_{i=1}^{m} \sum_{j=i+1}^{m} \frac{\partial}{\partial t} d(c_i, c_j) & \text{if } m > 1 . \end{cases}$$

As the distance measure d is computed at discrete time steps, the derivation with respect to time is performed numerically by computing differences. The derivative has to be smoothed because the distance measure has discrete values as well.

As mentioned earlier, another term $s_{\mathrm{S}}(\mathcal{G})$ depends on the size m of the group. If the group has too many members, the cooperative behavior decision will become computationally intractable. On the other hand, the objective function has to penalize small groups in order to avoid forming one-vehicle groups only. Hence, $s_{\mathrm{S}}(\mathcal{G}) = s_{\mathrm{S}}(m)$ should have a minimum at the desired group size m_0 and grow to both sides,

$$s_{\mathrm{S}}(\mathcal{G}) = (m - m_0)^2 . \quad (10)$$

The last term s_{T} evaluates the period of time which the vehicles already belong to the group. This will provide a hysteresis effect preventing a vehicle from changing its group too often due to small fluctuations in the other terms. Let t_i be the period of time since vehicle c_i joined group $\mathcal{G}$, and let t_{T} be a constant threshold. Then we define the temporal steadiness term to be

$$s_{\mathrm{T}}(\mathcal{G}) = \frac{1}{m} \sum_{i=1}^{m} \begin{cases} t_i & \text{if } 0 < t_i < t_{\mathrm{T}} \\ t_{\mathrm{T}} & \text{if } t_i = 0 \text{ or } t_i \geq t_{\mathrm{T}} . \end{cases} \quad (11)$$

Thus, a group gets an unfavourably high value of the objective function if a car just joins it, but a substantially lower value immediately after the join, preventing the car from changing the group once again within the near future.

B. Assignment of Vehicles to Cooperative Groups

Let $\mathcal{P}(C)$ be the set of partitions of n vehicles $C = \{c_1, \ldots, c_n\}$ into groups $\mathcal{G}_k$. The objective function for a partition $P \in \mathcal{P}$ is defined to be the sum of the objective functions of the groups in P,

$$s(P) := \sum_{\mathcal{G} \in P} s(\mathcal{G}) . \quad (12)$$

The optimal partition regarding the objective function (9) is given by

$$P^* = \arg \min_{P \in \mathcal{P}(C)} s(P) . \quad (13)$$

However, this minimization is computationally intensive because the number of partitions[1] is in $\Omega(2^n)$. Moreover, this global approach is difficult to realize in a distributed manner. Therefore we propose a local minimization in which only all pairs of neighboring groups are considered. Let $\mathcal{G}_1$, $\mathcal{G}_2$ be two neighboring groups and $\mathcal{G}_1 \cup \mathcal{G}_2 = \{c_1, \ldots, c_m\} =: C_{12}$ be the vehicles involved. Then the following partition is computed:

$$P_{\mathrm{L}}^* = \arg \min_{P \in \mathcal{P}(C_{12})} s(P) \quad (14)$$

This formal description includes as special cases the merging of $\mathcal{G}_1$ and $\mathcal{G}_2$ to a single group, the move of one or more cars from one group to another, and the split of a group into two or more smaller groups.

[1]The number of partitions can be stated precisely using the Bell numbers [26].

VI. Simulation Results

For a first evaluation of our formal modeling, we have developed a simulation prototype which computes the distance measure and realizes the formation of cooperative groups. The resulting group assignments in the simulated scenarios essentially correspond to our intuitive expectation. For example, a car always is in one group with oncoming cars in two-way traffic. Also, vehicles meeting at intersections are assigned to the same group (see Fig. 8). In dense traffic on highways, the cars are partitioned into groups of a reasonable size (see Fig. 9).

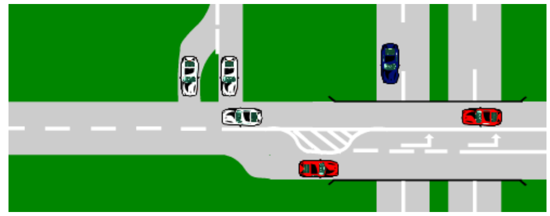


Fig. 8. Screenshot from the simulation prototype, showing some vehicles assigned to three distinct groups. As indicated by the colors of the cars, the three cars meeting at the intersection on the left of the image form one group. The two cars crossing each other in oncoming traffic belong to another group, together with three other vehicles not shown in this image. After crossing the oncoming vehicle, the car driving to the left will join the above-mentioned group at the intersection. The remaining vehicle that is situated on the highway below the bridge belongs to a third distinct group, as it cannot reach the other cars shown in an reasonable amount of time.

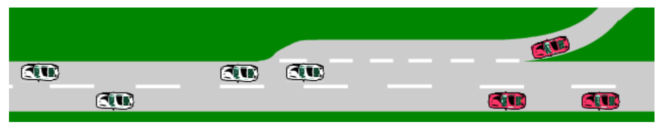


Fig. 9. A highway scenario from the simulation prototype. In these experiments, we have chosen the desired group size to be $m_0 = 4$ (cf. (10)). The objective function enables a reasonable partition of the vehicles into groups that do not grow too large, while it is ensured that cars maneuvering at close distance or overtaking each other belong to the same group.

VII. Conclusions and Future Works

In this article, we have proposed a new approach to increase traffic safety, namely the cooperation of cars which take coordinated actions. A top-down strategy has been presented, and as a first step the formation of cooperative groups based on a graph theoretic distance measure has been described and successfully tested within a simulation system. The subsequent situation recognition and behavior decision methods will be topics of future publications.

Concerning the distance measure, we plan to integrate the present implementation into a more powerful traffic simulator. This will enable a more comprehensive evaluation of our approach in a set of representative scenarios. Another direction of research will be the automatic optimization of the parameters in the objective function by supervised learning techniques using hand-labeled group assignments as ground truth.

VIII. Acknowledgements

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