A Cooperative Driver Model for Traffic Simulations

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Abstract—**In this paper, a cooperative driver model for a multi-agent traffic simulation is proposed. The model combines maneuver-based trajectory planning of the vehicles with a cooperative conflict resolving. The proposed model is able to provide a safe drive in complex traffic situations at the highest possible speed. The idea of the model and its feasibility have been verified in complex scenarios such as line change under heavy traffic, highway entering or highway crossing. Moreover, the developed cooperative driver model is being integrated with a human operated driving simulator that enables verification of the proposed model in mixed scenarios enriching the simulation for a human driver with highly cooperative background traffic; thus, providing a platform for further studies on benefits of assistive technologies. The paper provides description of the proposed model and its early evaluation on the selected scenarios in a multi-agent traffic simulation.**

I. INTRODUCTION

The amount of vehicles whether it concerns personal vehicles or trucks and insufficient highway networks capacity cause serious problems in modern time. Based on statistical information, a lot of car accidents occur every day and the number of accidents is still fast increasing. These are the reasons for demands for design and development intelligent highway systems, which would be able to address these problems on existing highway infrastructures.

Since 90s there is a research trend that is aimed at developing automated and autonomous systems improving safety and prevention or reduction of the accidents on existing highways. Results of this research indicate (through experimental demonstrations) that it is possible to achieve improvement in these challenging goals even under the given situations. One of the key results of this research effort is that the capacities of the highways are used inefficiently, because of reactive control performed by humans. Human drivers usually do not cooperate with the others and they have very limited or late knowledge about intentions of other vehicles. Hence, this fact provides a ground to design a cooperative driver model, which will enhance these features towards a more safety driving yet more efficient usage of the current highway infrastructures.

Regarding a cooperative behavior, let us remember a remark by Da Lio and colleagues ([1] and [2]). The authors pointed out that mankind used animals, and especially horses, as transportation systems for thousands of years. However, they have been replaced by motor vehicles in the last century, which causes that something has been lost: the intelligence of the animals and the interaction (cooperation) with humans (riders, in that case). In the recent book [3], Norman recalls the interaction between a rider and a horse as one example of how future intelligent interaction should work: "Think of skilled horseback riders. The rider reads the horse, just as the horse can read its rider. (...). This interaction (...) is of special interest because it is an example of two sentient systems, horse and rider, both intelligent, both interpreting the world and communicating their interpretations to each other." (quotation from Da Lio's paper and Norman's book).

This means that the cooperation (we focus on this aspect, even if we know that interaction regards also "competition") occurs between two "sentient" systems; in our case, one is the human agent (the driver) and the other one is not anymore the animal, but the machine agent. Literature provides many works of such a smart collaboration. The H-metaphor (i.e., the rider-horse metaphor) is one of the most relevant and was proposed by Flemish, originally in the aerospace domain, as a guideline for interactions between a vehicle and its driver [4]. Other examples are present in activities of Heide [5] and Inagaki [6], or in works related to the human-robot interactions (see [7], [8]) and adaptive automation (see [9], [10]), where both the human-agent and the machine-agent can initiate changes in the level of automation, producing modes of automation more closely tied to operator needs at any given moment.

It is also worth to remind that before deployment of any drive control system to the real traffic, it has to be experimentally validated in a simulated environment. Classical approaches of the traffic simulation are based mainly on a cellular automaton (CA) [11]. CA is a discrete model in time, space, and state variables. It consists of a regular grid of cells, each in one of a finite number of states. For each cell, a set of cells called its neighborhood is defined relative to the specified cell. Even though CA models are very efficient in large-scale network simulations, due to their simple design, we rather consider a continuous simulation of the vehicle's movement. It is because the CA is not able to provide such a simulation in conjunction with agent-based driver behavior modeling that supports a large scale of autonomous deliberative models.

In this paper, we propose an idea of the cooperative driver model that is based on a vehicle trajectory planning augmented by techniques from the domain of distributed artificial intelligence and already utilized in multi-agent systems. Altogether, it provides a multi-agent traffic simulation environment that can serve as a framework for evaluation of various cooperative planning strategies. Thus, it can provide a solid base for a further research towards defining representative quality metrics and comparison of different approaches.

II. REVIEW ON DRIVER MODELS

Basically, when talking about driver models, there are two main approaches: an engineering one and a cognitive one. Hereafter, we talk about the first type, while in Section III, we illustrate the second type. Modeling of the driver behaviour is studied for many years and the first concept was published in 1950 by Reuschel [12]. This model was a *car-following model*, i.e., the model that addresses only management of distances between cars using acceleration and breaks. The car-following model was adopted by many researchers, and therefore, this concept was widely studied. A representative model is the GM model, which was proposed by researchers at the GM Research Laboratories. Although this model had been one of the most popular models, another types of car-following models were proposed as: spacing model [13], Ohio model [14], psycho-physical model [15], and others. A general acceleration model was proposed by Gipps [16]. This model was designed for car-following and free-flow conditions. Gipps also published [17] the first lane change decision model. Another important model from the family of driver modeling is the gap acceptance model. This model decides whether a gap is suitable for lane change. Besides, an integrated driving modeling framework was proposed by Tomer [18].

The aforementioned models focus mainly on vehicle perspective while the cognitive type of the cooperative model focuses on vehicles in traffic perspective, which enables to consider a wider perspective and support for a complex cooperative behavior as it is illustrated in Section IV.

III. COOPERATIVE DRIVER MODEL

The cooperative driver model is inspired by the cooperative trajectory planning algorithms widely used in computational robotics for conflict-free navigation of autonomous vehicles (e.g., aerial vehicles [19]). This model enables to plan the trajectory of the vehicle moving on a highway and to cooperatively check the trajectories of the vehicles for conflicts [20]. If the conflict occurs the trajectories of the vehicles are adjusted to be conflict-free. This process is repeated to guarantee cooperative safe drive on the highway. This section gives an overview of the used highway model, trajectory planning algorithm and cooperative conflict resolution algorithm. Altogether, these three components form the proposed cooperative driver model that can be used in simulation. Examples verifying feasibility of the proposed model are given in Section IV.

A. Highway Model

The considered highway model in this paper is based on the model presented in [21], where a detailed description can be found; thus, only a brief overview of the model is presented here. A road consists of several types of curves, lines and arches. Bézier splines are used to represent all types of road parts as these splines represent a general solution that is well-know in computer graphics to model smooth curves. Bézier spline is a spline curve where each polynomial of the spline is in the Bézier form. In other words, a Bézier spline is simply a series of joined of Bézier curves, where the last point of the curve coincides with the starting point of the next curve. Each Bézier curve is described by a polynomial equation; thus, it is easy and efficient to calculate any point on the curve. The most common types of Bézier curves are quadratic and cubic. Curves described by a high degree polynomial are more expensive to evaluate, and therefore, if more complex shapes are needed, low order Bézier curves are patched together.

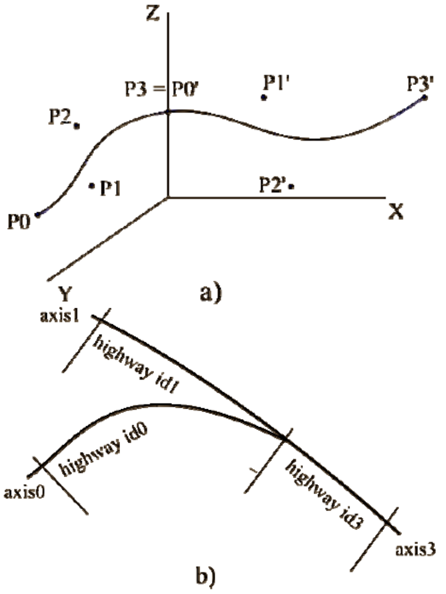

Fig. 1. The highway representation based on the Bézier curve. The Bézier curve in the 3D space (a) and the sample of highway crossing (b). [21]

In this work, we use cubic Bézier curves to represent a highway in the developed model. A cubic Bézier curve is defined by four points P_0, P_1, P_2 and P_3 in the plane or in three-dimensional space, see Fig. 1. The curve starts at P_0 going toward P_1 and arrives at P_3 coming from the direction of P_2. Usually, it will not pass through P_1 or P_2; these points are only there to provide directional information. The distance between P_0 and P_1 determines "how long" the curve moves into direction P_2 before turning towards P_3.

The main shape of each highway (represented by its axis) is generated by the Bézier spline and all such highways together form the whole highway network. The control point at which

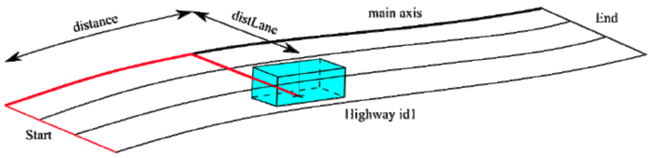

Fig. 2. Vehicle position representation on the highway segment [21].

two curves meet and one control point on either side must be collinear to guarantee smoothness of the highway. Each highway has at least one lane and lanes are parallel to the main axis spline in the xy plane, a bank of the whole highway is not included. The position of a vehicle on a highway is determined by its distance from the start of the highway, because each vehicle is moving only on the highway. The position of the car in the 3D world is computed from its distance by cast the distance to the polynomial form of the spline, see Fig. 2.

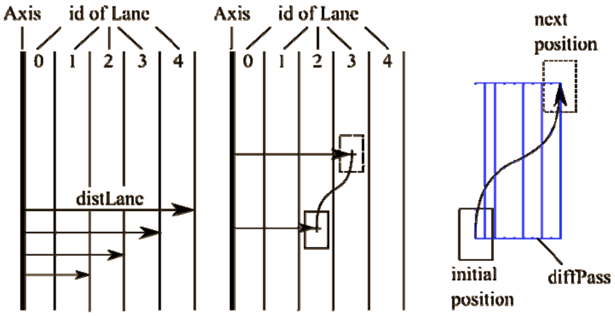

Fig. 3. Details of highway and its lanes. The representation of vehicle position on the highway (left) and the lane change (middle and right) [21].

Regarding the vehicle position on a multi-lane highway, the position is specified by two distances. The first is the distance of the vehicle's center from the start of the highway. The second distance is between the vehicle's center and the main axis of the highway center. The distance is denoted as *distLane*, see Fig. 2. In Fig. 3, representation of the vehicle's position and change of the lane is shown. The vehicle increases its distLane position and thus effectively changes the lane.

B. Vehicle Trajectory Planning

The considered trajectory planning algorithm operates in the maneuver space. Possible maneuvers of the vehicle are designed to correspond to basic maneuvers of the vehicle on a highway. The parameters of each maneuver are: the start time of the maneuver, the velocity, position and the lane of the vehicle at the beginning of the maneuver, and an acceleration of the vehicle during the maneuver. The output parameters of a maneuver are computed according to the type of the maneuver using the relevant car dynamic model. The maneuver transforms the state of the vehicle. All the maneuvers are defined by the duration of their execution. So, the maneuver can be represented in a 3-dimensional space, where the dimensions are lane, distance and time; hence, the maneuver forms a 3-dimensional object in this space. The considered types of the maneuver are following:

- **Straight** – vehicle keeps the lane for a certain period. There is no acceleration so neither the velocity is changed.
- **Change lane left** – vehicle changes the lane to the left. It is assumed the velocity of the vehicle is constant during this maneuver. The size and duration of this maneuver may depend on the vehicle velocity.
- **Change lane right** – vehicle changes the lane to the right. It is assumed the velocity of the vehicle is constant during this maneuver. The size and duration of this maneuver may depend on the vehicle velocity as for the previous type.
- **Acceleration** – vehicle keeps the lane for a certain period. The acceleration is constant until the maneuver ends or the maximal velocity of the vehicle is reached.
- **Deceleration** – vehicle keeps the lane for a certain period. The deceleration is constant until the maneuver ends or the vehicle stops.

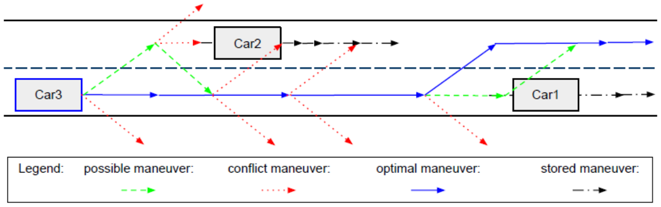

Fig. 4. Trajectory planning example based on maneuvers space search [20].

The maneuvers are organized into a sequence representing the trajectory plan. The maneuvers are joined in the plan to form a smooth trajectory, i.e., all input parameters of each maneuver have to correspond with the output parameters of the previous maneuver. The plan is built by searching the maneuver space using the A* algorithm [22]. The plan is constructed on the desired time horizon in such a way that the vehicle reach the target lane (for planning an overtaking, exiting or entering the highway) and the speed of the vehicle is as close as possible to the desired vehicle speed, e.g., the maximum speed limit for the given type of the vehicle on the highway. During the search, the algorithm respects the layout of the highway (the number of lanes and their changes) or known obstacles to avoid dangerous maneuvers. Examples of dangerous maneuvers are maneuvers that end out of the highway, braking the traffic rules or intersect with an obstacle. The cooperative planning method is used to avoid collisions with other vehicles. An example of the maneuver based plan is shown in Fig. 4. The method is described in the next paragraphs.

C. Cooperative Trajectory Planning

The goal of the cooperative trajectory planning is to find trajectories for two or more vehicles that are conflict-free in space and time. The cooperative driver model uses an iterative algorithm that generates trajectories for all vehicles, checks the trajectories for eventual conflicts and iteratively resolves the conflicts [20].

The initial step is that each vehicle plans its own trajectory as described in the previous section. Once the trajectory is planned, it is broadcasted to all other vehicles and all trajectories are then tested for spatio-temporal conflicts as follows.

First, the general plan conflict is examined. Since all the plans' beginnings are situated at the actual time it is necessary to test only the spatial overlap of particular plans (trajectories). This can be simplified to one-dimensional evaluation of the beginning and ending distances of the plans on the highway, i.e., if the plans are situated on the same segment of the highway. If such potentially overlapping plans are identified, the plans are further tested on a maneuver-to-maneuver basis.

Let considers the maneuver as a 3-dimensional object in the lane×distance×time space, then an intersection between two such objects represents a possible conflict of the corresponding maneuvers. The conflict can be examined as follows. For each pair of maneuvers the time intersection is tested first. If the time windows (time between the start and end of the maneuver) are overlapping, possible position intersection is tested. If the bounding boxes (based on lanes and starting and ending distances) are overlapping the linear time approximations of the precise positions inside the maneuvers are tested against the defined safe distance, which can be different for a different type of the vehicle.

After the collision tests, the cooperative algorithm starts with the soonest detected conflict. The algorithm generates a set of alternative trajectories for vehicles in the conflict in the way that a new trajectory is not colliding with any other vehicle trajectory at the time before the conflict being solved. Afterwards, the sets for both vehicles are combined to create all possible pairs of trajectories (Cartesian product of the sets) and each pair is checked whether a mutual collision persists. The most suitable conflict-free solution is selected according to the defined criterion[1], while the solution is allowed to be conflicting in the time greater than the time of the conflict being solved. When a single collision is solved, the next soonest collision is selected and the process is repeated. It is expected that this approach converges to the conflict-free solution [19]. Unfortunately, on the finite highway the described algorithm may lead to the situation when the Cartesian product of the trajectories set contains no conflict-free solution. In such a case, a safe maneuver has to be performed to guarantee safety of the vehicles.

The guarantied safe maneuver to avoid a conflict of two vehicles on the highway is to either change the lane or adjust the speed. To demonstrate the main difficulty of finding such a maneuver, imagine the following scenario. Let assume none of the two conflicting vehicles can change lane (it would create a conflict, which would happen sooner then the current one). Then, the vehicles have to change their speeds, which ideally means the first vehicle (the ahead of the second vehicle) will accelerate or the second vehicle will slow down. The first vehicle often cannot accelerate because it is going its highest speed or because of another vehicle in front of it. This means the conflict has to be solved by the second vehicle. Regarding the above described algorithm the second vehicle is unable to decelerate at this moment because it would cause immediate conflict with another vehicle behind it. Hence, the safe maneuver algorithm can suggest a deceleration maneuver from the last non-conflict node of its plan, but this maneuver can cause a conflict at the same time as the current conflict time that is trying to be resolved. When this happens, the original peer-to-peer algorithm fails.

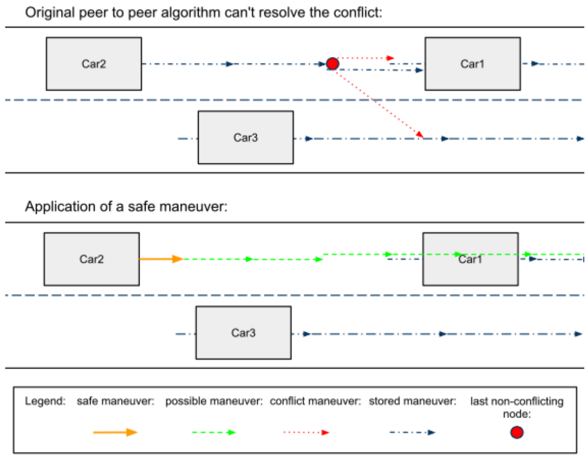

Fig. 5. Safe maneuver application as a result of failure of the cooperative conflict resolution [20].

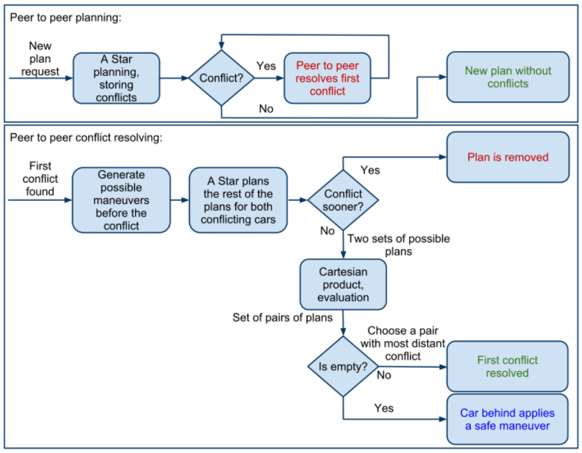

Fig. 6. Cooperative trajectory planning algorithm used in the cooperative driver model [20].

The proposed solution of the sketched issue is as follows. When a pair of two conflicting vehicles is not able to resolve the conflict, the second agent (the vehicle that is at the back, i.e., it has a shorter distance traveled), creates a safe deceleration maneuver starting from the current vehicle state. Then, the agent creates a plan starting with the safe maneuver, using the A* algorithm, and the peer-to-peer algorithm is repeated. If it is still unable to resolve the soonest conflict (which is different from the one before the application of the safe maneuver), the agent adds a second safe maneuver after the first one and creates the plan again with the A* algorithm. This process can be repeated until a non-conflicting plan is created. An example of the situation is visualized in Fig. 5, where the Car2 is trying to create a non-conflicting plan, which can be created only by applying a safe maneuver. The whole cooperative algorithm with the safe maneuver application is depicted in Fig. 6.

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[1] Moreover, few candidate solutions can be visualized to the driver, which can selected the best solution according to the current situation and preferences.

IV. EVALUATION

The cooperative driver model is developed with the aim to solve scenarios where a non-trivial interaction between vehicles is needed. In the dense traffic, it is not easy to open a gap or change multiple lanes while keeping the highest possible speed. Example of such complex situation can be (i) entering the highway in high traffic, (ii) lane ending on the dense highway, or (iii) exiting the highway with the need of crossing multiple lanes. A simulation platform is desirable to allow demonstration and assessment of the cooperative functions, e.g., for the Lane Change Assistant. Moreover, such a platform can also serve as a framework for evaluating various strategies how to deal with conflicting situations and how to measure quality of suggested solutions. Regarding these needs, the proposed cooperative driver model has been implemented in a multi-agent traffic simulator providing an initial verification of the proposed concept. After that the model can be tested in a more complex scenarios with a human operated driving simulator. A description of the simulators and example of the evaluation scenarios are presented in the following sub-sections.

A. *Traffic Simulation*

The multi-agent simulator is able to simulate a high number of independent agents – vehicles. Each agent drives its car according to the instructions provided by the cooperative driver model. A wide range of parameters (e.g., velocity profiles, distance traveled, the number of lane change maneuvers, the number of acceleration/deceleration maneuvers, traffic density, etc) can be measured within this simulation, which makes the simulator a suitable platform for a further evaluation of the different driver assistive technologies in various situations.

One of the situations example is the cooperative entry-lane scenario depicted in Fig. 7. The vehicles on the highway open the gap in advance to enable entering vehicles change the lane in the full speed before the end of the entering lane. For such high-speed maneuvers the cooperation is needed to synchronize the vehicles and their speeds at the right time and space. This cooperation would not be possible without the proposed cooperative trajectory planning algorithm.

Fig. 8 shows a schematic view of a more complicated situation of highway crossing. The figure shows left half of the cross that continues with symmetric (mirrored) layout. Vehicles enter the scene in a random lane of one of the two highways. Each vehicle chooses randomly a target highway and the final lane (out of the picture to the right). This setting introduces the scenario in which the vehicles have to change the lane before the particular split and also before the end of the middle two-lanes for reaching the final highway. Again, the cooperative driver model is able to provide a fluent safe traffic with maximized vehicle speeds.

B. *Driving Simulation*

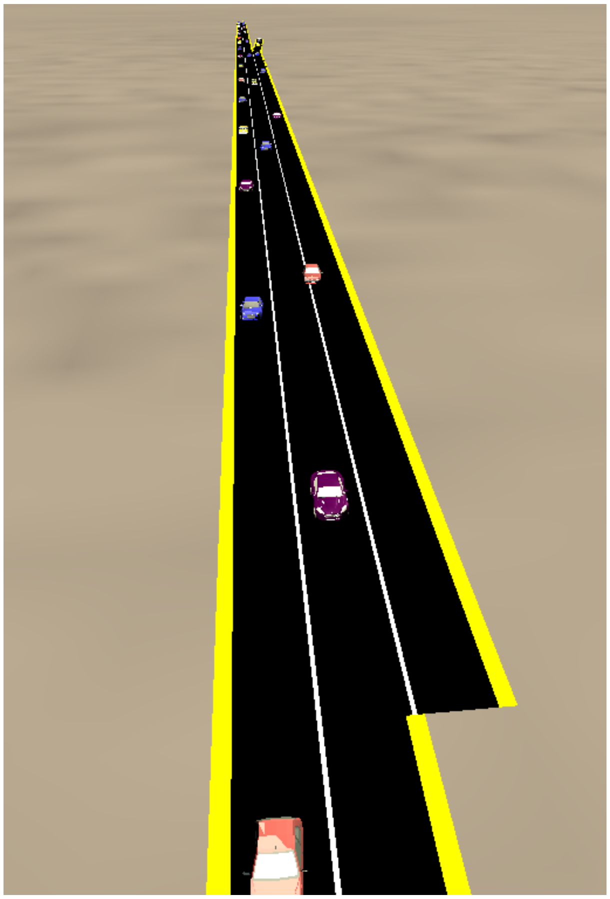

Fig. 7. A simulation of the cooperative entry-lane scenario (3D view).

To verify the model in more realistic conditions we intend to integrate the simulation with a human operated driving simulator. The background traffic fully utilize cooperative driver model, but the human operator may provide uncertainty in the trajectory plan execution and errors in the cooperative collision avoidance mechanism. When one of the vehicles does not follow the planned route, all others have to continuously replan their trajectories to adapt to the new situation; thus, the effectiveness of the cooperative driver model and user acceptability of it can be studied.

Fig. 9. Driving simulator.

For such an evaluation we consider the driving simulator[2]

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[2] Owner of the simulator is Reggio Emilia Innovazione, http://www.reinnova.it/en/.

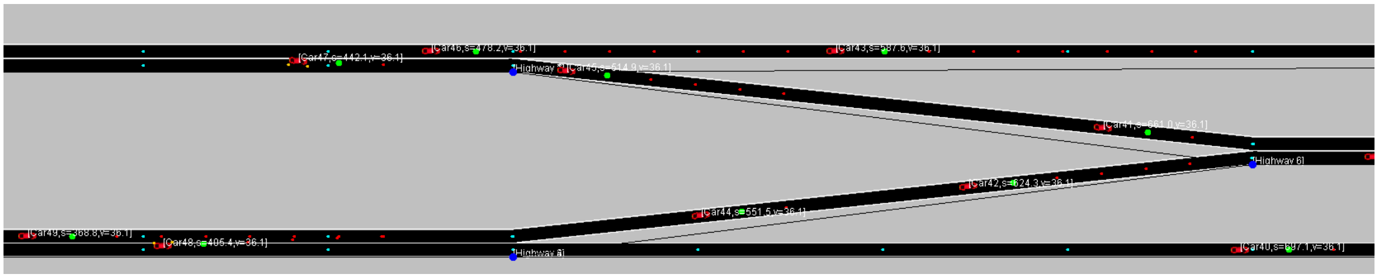

Fig. 8. Example of the simulation of the cooperative highway cross scenario (schematic 2D view).

shown in Fig. 9. The system is a fixed based simulator that comprises a mock-up of a car with real driving controls, specifically a seat, steering wheel, pedals, gear, handbrake and a digital simulated dashboard displaying a traditional instrumental panel, with the RPM visualization, speedometer and vehicle subsystem lamps. The steering wheel, in particular, is a steer-by-wire system with reconfigurable stiffness and wheels transmission ratio. According to the type of road and the vehicle dynamic, the simulator provides feedbacks to the driver through vibrations reproduced on the steering wheel and on the seat.

V. CONCLUSION

This paper presents our early results on the proposed cooperative driver model for a multi-agent traffic simulation. The driver model is built on the bases of a highly cooperative approach utilizing methods from the field of distributed artificial intelligence. Each vehicle is able to plan its trajectory using a set of parametrized maneuvers. Detected spatio-temporal conflicts between planned trajectories are cooperatively resolved and the proposed technique ensures safe drive at the highest possible speed in complex scenarios with a dense traffic that would not be possible without the introducing the planning and cooperation.

Examples of the verifying scenarios where the presented cooperative driver model demonstrates its benefits in the multi-agent simulator are presented. Besides, the described human operated driving simulator is being developed and validation of the cooperative driver model in mixed scenarios is expected. Moreover, the simulation platform being developed provides a suitable environment for further evaluation and benchmarking assistive technologies that will also allow to study different solution quality metrics for difficult scenarios where an appropriate solution depends on the complex situation awareness. Such an evaluation and research is a subject of our future work.

ACKNOWLEDGMENT

This work has been supported by the Ministry of Education, Youth and Sports of Czech Republic within the grants No. 7H11102 and No. LD12044 and by the ARTEMIS Joint Undertaking under the number 269336-2.

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