CZECH TECHNICAL UNIVERSITY
IN PRAGUE

The Faculty of Electrical Engineering

BACHELOR THESIS

Noncooperative collision avoidance of road vehicles

Prague, 2011 Author: Martin Schaefer

Prohlášení

Prohlašuji, že jsem svou diplomovou (bakalářskou) práci vypracoval samostatně a použil jsem pouze podklady (literaturu, projekty, SW atd.) uvedené v přiloženém seznamu.

V Praze dne 26.5.2011

podpis

Poděkování

Rád bych využil příležitosti a poděkoval v první řadě vedoucímu práce panu Ing. Antonínu Komendovi za trpělivé vedení, cenné rady a vstřícný přístup. Jemu a panu Ing. Vokřínkovi děkuji za čas a úsilí vložené do projektu Highway2. Tímto též děkuji za příležitost podílet se na zajímavém a snad nejen mně osobně přínosném projektu. Dík patří i kolegům spolupracujícím na projektu Pavlovi Janovskému, Aleši Fraňkovi a Karlu Jalovci. Vážím si spolupráce, která přinesla nejen mnoho nápadů, ale poskytla i dobrou zpětnou vazbu a reflexi.

Poděkování patří též všem těm, kteří mne podporovali v průběhu práce. Zejména pak děkuji svým nejbližším. Speciální dík směřuji všem těm, kteří si opakovaně vyslechli, že stále bourají a přesto pevně věřili, že přestanou.

Abstrakt

Tato bakalářská práce se věnuje návrhu a implementaci nekooperativních metod vyhýbání silničních vozidel. Metody jsou navrženy jako součást simulátoru dálnice. Simulátor, jehož popis je obsažen v této práci, je založen na multi-agentních technologiích.

Představeny jsou dvě nekooperativní metody. První z nich je založena na predikci a plánování manévrů s využitím algoritmu A*. Principem druhé metody je hlídání bezpečné vzdálenosti. Obě metody byly prověřeny při simulaci. Byly použity rozličné scénáře. Metoda založena na hlídání bezpečné vzdálenosti je také porovnána s kooperativní metodou a metodou založenou na strojovém učení. Nejvíce zohledněnými parametry byly schopnost zamezení kolize a hustota provozu. Součástí práce je také popis problému zúžení na dálnici.

Abstract

The thesis deals with the design and implementation of noncooperative collision avoidance methods. The methods are implemented as a part of the highway simulator. The simulator, described in the thesis, is based on the usage of multi-agent technologies.

Two noncooperative methods are introduced. The first one is based on the basic prediction and planning maneuvers using A* algorithm. The principle of the second one is the observance of the safe distance. The both methods were validated in simulation. The various scenarios are used. The method based on the safe distance observance is also compared to the cooperative and machine learning based methods of deconfliction. The most regarded parameters are the ability to avoid collisions and the traffic flow. The problems related to the highway narrowing are also described in the thesis.

České vysoké učení technické v Praze
Fakulta elektrotechnická

Katedra kybernetiky

ZADÁNÍ BAKALÁŘSKÉ PRÁCE

Student: Martin Schaefer

Studijní program: Elektrotechnika a informatika (bakalářský), strukturovaný

Obor: Kybernetika a měření

Název tématu: Nekooperativní metody vyhýbání silničních vozidel

Pokyny pro vypracování:

1. Nastudujte tématiku nekooperativního vyhýbání silničních vozidel.
2. Seznamte se s agentní platformou a simulátorem.
3. Navrhněte metody nekooperativního vyhýbání vozidel.
4. Implementujte a validujte navržené metody pomocí simulace.

Seznam odborné literatury:

[1] Jiránek, J.: Non-cooperative Agents for Cars Drive Simulation. Praha, 2009.
[2] Komenda, A.: Použití multi-agentního systému pro nekooperativní vyhýbání letadel. Praha, 2007.

Vedoucí bakalářské práce: Ing. Antonín Komenda

Platnost zadání: do konce zimního semestru 2011/2012

prof. Ing. Vladimír Mařík, DrSc.
vedoucí katedry

prof. Ing. Boris Šimák, CSc.
děkan

V Praze dne 4. 2. 2011

Czech Technical University in Prague
Faculty of Electrical Engineering

Department of Cybernetics

BACHELOR PROJECT ASSIGNMENT

Student: Martin Schaefer

Study programme: Electrical Engineering and Information Technology

Specialisation: Cybernetics and Measurement

Title of Bachelor Project: Noncooperative Collision Avoidance of Road Vehicles

Guidelines:

1. Study the theme of noncooperative avoidance of vehicles.
2. Get to know the agent platform and the simulator.
3. Design methods of noncooperative avoidance of vehicles.
4. Implement and validate designed methods by simulation.

Bibliography/Sources:

[1] Jiránek, J.: Non-cooperative Agents for Cars Drive Simulation. Praha, 2009.
[2] Komenda, A.: Použití multi-agentního systému pro nekooperativní vyhýbání letadel. Praha, 2007.

Bachelor Project Supervisor: Ing. Antonín Komenda

Valid until: the end of the winter semester of academic year 2011/2012

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE Fakulta elektrotechnická L.S. -4-

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Prague, February 4, 2011

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Chapter 1

Introduction

Driving is an activity many people do every day. The activity that can be very demanding. The failure of driver can lead to serious consequences. While the human factor causes majority of the collisions, the usage of automatic control systems seems to be relevant. The autonomous systems independent to the human factor are possible future of the area of controlling the vehicles. The road vehicles are not exception.

The thesis deals with the noncooperative collision avoidance of road vehicles. The highway simulator is chosen to be the environment to implementation and validation of designed methods. The highway represents the environment that is generally simple to be described and simulated.

The artificial intelligence offers several methods to control the vehicles. The advanced methods are usually based on the cooperation of the entities. The noncooperative methods are used in the situation if the cooperation is not possible. The term of cooperation, as it is used in the context of this thesis, is meant to be the intentional communication. The observance of the behaviour and expectation of a will to avoid collision is not considered to be cooperation. The multi-agent system is used to simulate a part of a highway.

The theoretical background of multi-agent systems is introduced in Chapter 2. The highway simulator is presented in Chapter 3. The designed and implemented noncooperative methods are described in Chapter 4. The Chapter 5 deals with validation of methods in simulation.

Chapter 2

Multi-agent systems

2.1 Multi-Agent Systems

This chapter deals with the basic description of the multi-agent system (MAS) theory. The multi-agent system theory is a part of the field of interest of the artificial intelligence. The multi-agent systems are suitable to model many real world systems. The common features of these systems are according to [Kubík, 2004] decentralization of control in system, autonomy of entities, robustness and adaptability to environment changes. The research in the multi-agent area is wide. Let us mention only the areas closely related with this thesis. These are MAS architecture, the coordination and cooperation in MAS, planning in MAS and agent-based software engineering.

2.1.1 Agents

The MAS compounds of multiple agents. The agent as a component of the system is to some extent autonomous entity. The definition of an agent according to [Ferber, 2001] follows.

> An agent can be a physical or virtual entity that can act, perceive its environment (in a partial way) and communicate with others, is autonomous and has skills to achieve its goals and tendencies. It is in a multi-agent system (MAS) that contains an environment, objects and agents (the agents being the only ones to act), relations between all the entities, a set of operations that can be performed by the entities and the changes of the universe in time and due to these actions.

The agents can be divided into categories according to various aspects. As for example, aspects like architecture, rationality level, cooperation level and others.

Chapter 3

MAS platform and simulator

Following chapter describes the agent based Alite toolkit and the highway simulator designed using the toolkit.

3.1 Alite

The Alite is a light-weight agent-based toolkit developed and used by Agent Technology Center. The Alite is designed to make easier developing of multi-agent systems and simulators. The toolkit is very variable. Alite itself is described on the project site [ATG, 2011b]. Our concrete usage of the it is described in the following Section 3.2.

3.2 Simulator

3.2.1 Development

The highway traffic simulator is being developed using the Alite toolkit. The design and implementation of the simulator core was part of the Highway2 project supervised by Ing. Antonín Komenda and Ing. Jiří Vokřínek. The project members Aleš Franěk, Karel Jalovec, Pavel Janovský and Martin Schaefer cooperated on design and implementation of the highway traffic simulator core. The goal of this project was to create agent-based simulator using Alite toolkit, that would be modular and would offer further possibilities to implement various methods of vehicle deconfliction. The structure of the simulator described in Section 3.2.3 allows to evaluate various methods of control on the common base. The important feature of the simulator is layered structure (see Section 3.2.4). This structure lets to design deconfliction algorithms in specific layer while being built on the structure of lower layers. The lower layers can be used by various algorithms of higher layer. This feature provides the modularity of the system. Let us to introduce the theses involved in designing and implementing the control algorithms. This thesis deals with non-cooperative methods, Pavel Janovský works on cooperative methods and Aleš Franěk uses machine learning methods. That is also shown in Figure 3.1. The principles of the methods especially the differences between them are described in the Chapters 4 and 5.

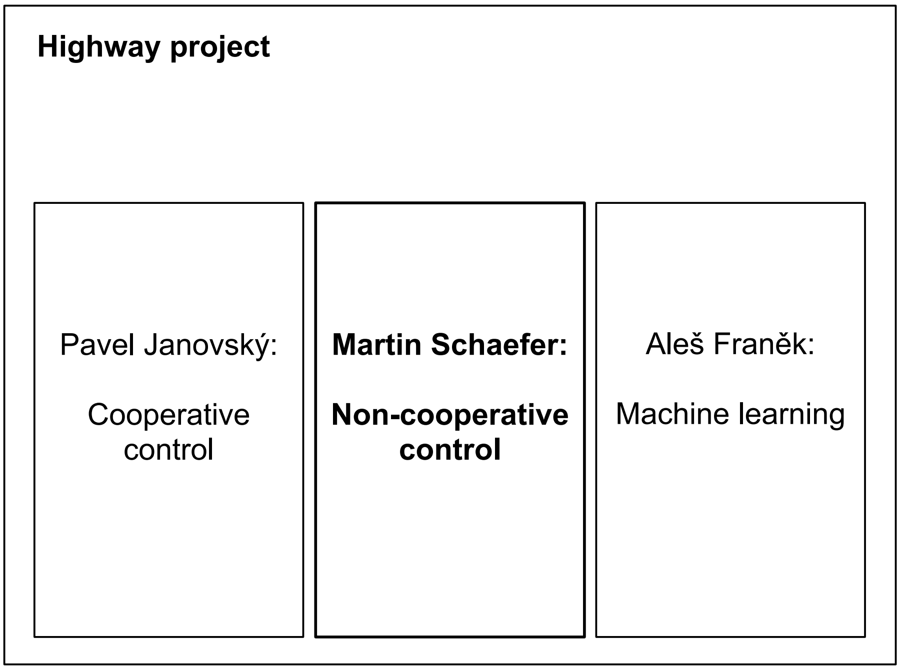

Figure 3.1: Highway2 project - control methods.

3.2.2 Alite architecture

We will describe the structure of the simulator. The structure is based on the Alite so the skeleton of the simulator comes from Alite architecture. The simulator is an event based, so the core of the simulator is event queue. Synchronization and event processing is provided by the Alite. The simulation world consists of entities. These are created by Creators. State representation of the entities in the world is saved in the storages. The entities can perceive and affect their state represented in the storages. They can perceive through the sensors and affect the storages (perform actions) through the actuators. The basic visualization is provided by Alite as well. The visualization itself is independent part of the simulator so the visualization does not affect the simulation, it can be eventually turned off. The simplified scheme of Alite simulation is in the Figure 3.2.

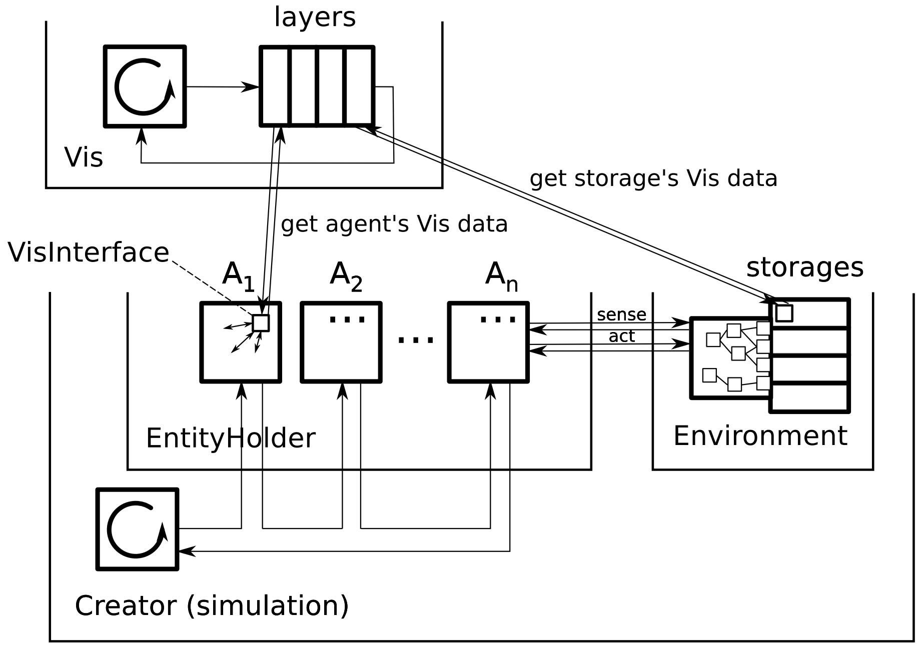

Figure 3.2: Simplified scheme of simulation [ATG, 2011b].

3.2.3 Highway architecture

The entities in the highway simulator are static or dynamic. The static part of the world represents highway that consists of segments. The vehicles are dynamic. It means that the agent representing vehicle have its sensors and actuators. The definition of an agent is in the Section 2.1.1. The principle of the agent-actuator-sensor structure is shown in the Figure 3.3. As we said before the sensors and actuators are used to sense or act - perceive or affect the storages. The storages representing entities correspond to static and dynamic division as well. The *HighwayStorage* holds all the information about the static part of the world - about highway. The *CarStorage* holds all the information about dynamic part of the world - about vehicles. It results in statement that both storages are sensed by sensors of vehicles but during the simulation only the *CarStorage* is being changed by actuators of the vehicle entities. The change of the storage, let us say the movement of the vehicles is provided by periodical invocation of an event, let us call it a STEP event. The STEP event is handled by the entities. Each entity, respecting the specifications of itself using the system of sensors and actuators, changes its position saved in the *CarStorage*. Every vehicle entity (every car agent) is responsible for itself, which respect the idea of decentralization of the highway control. The simulation step is defined by the period between STEP event invocations.

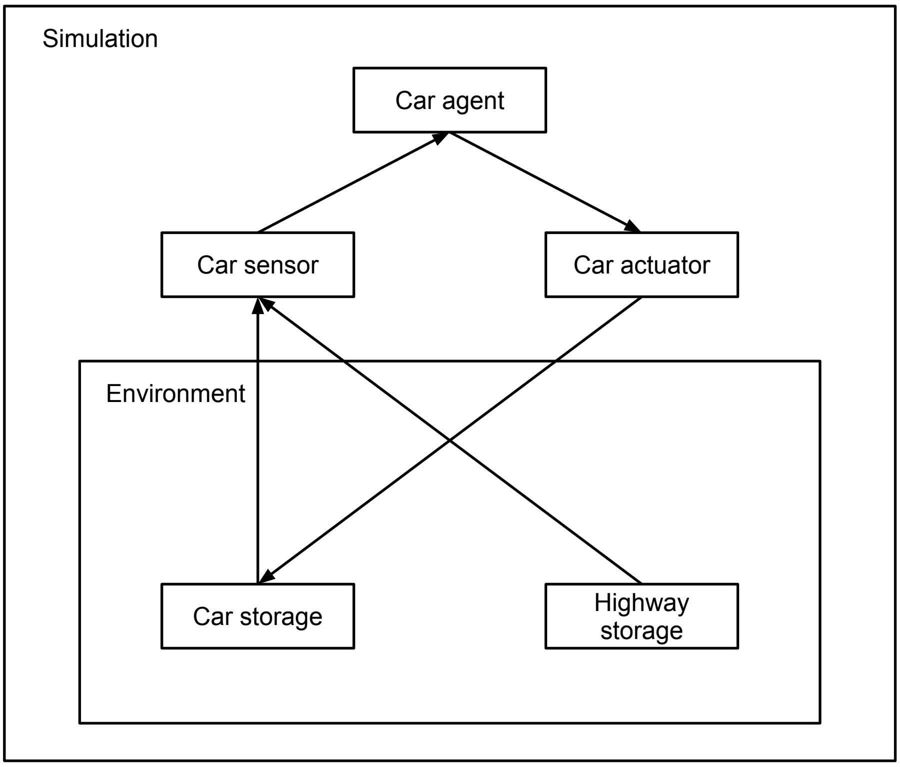

Figure 3.3: Agent, sensor and actuator [Janovský, 2011].

3.2.4 Structure of sensors and actuators

The simulator is designed to be modular and should offer clear API for developers. While the driving or controlling the vehicle is very complex task, the structure of sensors and actuators is separated into three layers. The layered structure is shown in the Figure 3.4.

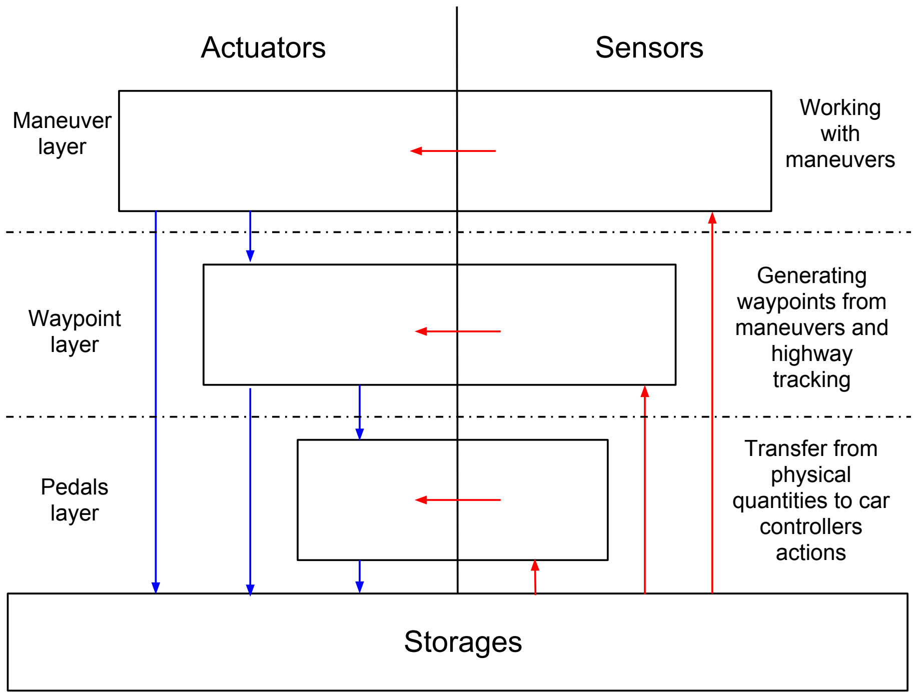

Figure 3.4: Three layer structure of actuators and sensors.

The structure consists of three layers. Each layer consists of sensor and actuator. Each layer has its specific task. The higher layer the higher level of control. A higher layer is an extension of the lower ones. The higher layer is not required by lower layer, so the absent of higher layers has no effect on behaviour of the lower layers. On opposite the higher layer requires lower layer to perform specific action related to driving. In Figure 3.4 we observe that requirement on lower layers comes from the actuators, not from the sensors. There are actions of higher layer actuators that perform actions of lower layer actuators. The simple example to clarify the idea is that the vehicles has to perform turning left, straight driving and turning right to perform higher action overtaking. The sensor provides the information about the environment respecting the layer that is part of. The sensors in contrast to actuators do not require lower layer sensors because all of the sensors sense directly from the storages. That was the explanation of vertical arrows in Figure 3.4, let us show the meaning of the horizontal ones. The horizontal arrows represent the usage of sensors by actuators of the same layer. The usage of sensors by actuators make possible to enrich the actuator with intelligent behaviour. The horizontal arrow closes the circle actuator - storage - sensor. The feedback is involved. It provides the possibility of control in each layer, the control independent on the higher layer. For instance it can be lane tracking according to the sensed lane profile. That is independent to the desires of driver (representing higher layer), the desires like an acceleration, lane changing and similar ones. This feature is more described in 3.2.6.

3.2.5 Maneuver layer

The maneuver layer is the highest layer of the structure (Figure 3.4). This is the layer where the deconfliction algorithms are designed and implemented. The name of the layer implies that the layer works with maneuvers. The maneuvers are described individually in the Section 3.2.5.1. The layer is designed for the purpose of simplification of the deconfliction algorithms. The simplification consists of defining the bases of maneuvers. The simple maneuvers are defined and the movement of vehicles is defined as a sequence of these maneuvers. The profile of the highway is not concerned. The highway is linear in the context of the maneuver layer. The position of a vehicle is represent by two values. The values are the distance from the defined start of the highway and the number of the current lane. This makes possible to discretizate the movement into the simple maneuvers. The discretization of the movement leads to the reduction of the state space of the vehicle while planning. The basic processing model of the layer is following. The sensor of the maneuver layer sense the state of the vehicle. It can also provide information about the environment - the highway and the other vehicles in the neighbourhood. According to the information from sensor the agent decides what to do next. The action processed by the actuator of the maneuver layer is usually to perform a maneuver. The agent, the process of decision making, planning is described in more details in the Chapter 4.

3.2.5.1 Maneuvers

The maneuvers in the simulator are designed to correspond the basic maneuvers of a vehicle on a highway. The maneuvers are defined by several parameters. All the maneuveurs are defined by the duration of their execution. Each type of maneuver has the constant duration. The input parameters of each maneuver are the start time of the maneuver, the velocity of the related vehicle at the start of the maneuver, the position of the vehicle at the start of the maneuver and the lane the vehicle is in at the start of the maneuver. Another important parameter is a constant acceleration of the vehicle during the maneuver. The output parameters of an maneuver are computed according to the type of the maneuver using the relevant input parameters. The maneuver transforms the temporary state into the next one. The maneuver types are following.

Straight maneuver

The lane of the vehicle is not changed. There is no acceleration so neither the velocity is changed.

Turning left maneuver

The lane of the vehicle is changed by one to the left. The velocity is constant.

Turning right maneuver

The lane of the vehicle is changed by one to the right. The velocity is constant.

Acceleration maneuver

The lane of the vehicle is not changed. The acceleration is constant until the maneuver ends or the maximal velocity of the vehicle is reached.

Deceleration maneuver

The lane of the vehicle is not changed. The deceleration is constant until the maneuver ends or the vehicle stops.

3.2.6 Waypoint layer

The layer under the maneuver layer is the waypoint layer. The waypoint layer as the other layer consists of the sensor and actuator. The purpose of this layer is to perform a maneuver and add the highway profile tracking. It means that the curves on the highway are concerned. The waypoint layer creates a sequence of waypoints that are generated according to the maneuver to execute and the highway profile. The maneuver to execute is the result of the maneuver layer process. The maneuver is sent to the waypoint layer to be performed at the specified time. The waypoints are generated according to the parameters of the maneuver. The sensor provides the information about the highway profile. The influence of the profile is added to the waypoints of the maneuver. This layer allows the vehicle to follow the universal profile of the highway. The waypoints are generated at the start time of the related maneuver. Until the next maneuver execution request is sent by the maneuver layer the vehicle drives through the waypoints. The cyclic sensing and performing actions creates feedback control cycles that navigate the vehicle through the waypoints.

3.2.7 Pedals layer

The third layer of the structure is the pedals layer. The idea of the layer is the connection of the virtual driver and the model of the vehicle. That is where the name of the layer comes from. The pedals are the controllers used to physically drive the vehicle in reality. So usually the models of vehicles are controlled by the setting of angles of pedals or steering wheel. The pedals layer transfers the velocity and the direction vector to the angles of the related controllers. This fact makes the layer more simple, the cyclic sensing is not required. The importance of the layer should be more evident when using various and more complex vehicle models.

Chapter 4

Control Methods

The following chapter deals with the description of the control methods. The design and the implementation of the non-cooperative methods of deconfliction are the main tasks of this thesis. To put the non-cooperative methods into the context, the general specification of the control methods is introduced.

4.1 Planning methods

The control methods or algorithms are designed to substitute the human in function of the controlling. The examples are planes or vehicles. The very basic requirements on the driver's or pilot's activity are similar. The requirements as achieving the target while avoiding the collision. The ATG showed the potential of the methods in the Agent-Fly project [ATG, 2011a]. The deconfliction methods used on planes were successfully implemented and tested in simulation. The similarity of the problem being solved by methods in the project AgentFly and the problem of deconfliction on a highway leads to the idea of usage similar methods even on vehicles. The usage of multi-agent system for non-cooperative deconfliction of planes is topic of the [Komenda, 2007]. The method is briefly described by the following sentence.

> A method for non-cooperative collision avoidance in multi-agent environment based on spatial planning with use of the A* algorithm, linear prediction of collision points and dynamic forbidden zones ... .

While studying the specifications of the method, the differences between plane environment and highway are concerned. The most problematic assumption is that the trajectories must be planned to avoid the forbidden zones. The forbidden zones represent the area of the possible collision. The shape of the dynamic forbidden zone of a plane is in Figure 4.1. The forbidden zone, that comes from the possible trajectory of a related entity, would be similar for the vehicle. The main difference is that the vehicle's trajectory is planar. The highway in contrast to the air space is much more limited space.

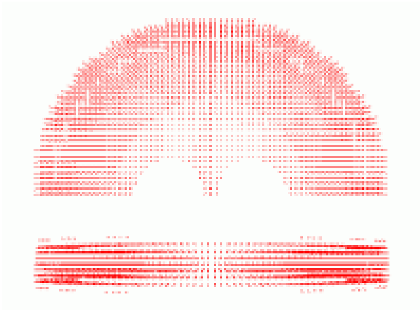

Figure 4.1: Forbidden zone [Komenda, 2007].

In general the vehicle overtaking another vehicle cannot avoid the forbidden zone of the vehicle being overtaken. The restriction of the forbidden zone of a vehicle being overtaken would solve the problem. Due to absence of the communication. It is necessary to expect that other vehicles follow some rules. The rules that would restrict the colliding lane change of the vehicle being overtaken. While the adversary behaviour is not primarily assumed, the will to avoid the collision is expected. The following methods are based on these principles.

4.1.1 Non-cooperative spatial planning method

The first non-cooperative method of deconfliction is based on the planning with use of A* algorithm and prediction of forbidden zones. The design was adapted to be implemented as a part of the maneuver layer described in the Section 3.2.5. The plan is defined as a sequence of maneuvers (see Section 3.2.5.1). The forbidden zone, representing the area where the vehicle can occur, is represented by consequence of maneuvers. The area of maneuver is defined by its position and lane. The area of maneuver as well as forbidden zone represents the area where the vehicle can occur while executing the maneuver. This is the reason why maneuvers can be used as a representation of forbidden zones.

The method itself is divided into two main parts. The first is the prediction of each vehicle's plan (maneuvers) and the second is the planning of consequence of maneuvers, that does not collide with any maneuver predicted.

4.1.1.1 Prediction

The prediction is used because a non-cooperative method does not allow the use of communication to get the other vehicles plans. The plans are predicted according to the states of the related vehicles. The vehicles in the range of visibility are provided by sensors of maneuver layer. The step is illustrated in Figure 4.2

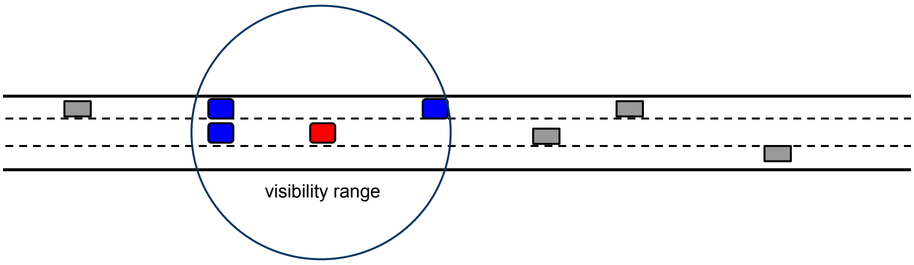

Figure 4.2: Sensing the vehicles in the visibility range.

The information used by the predictor is a subset of the parameters defining the state of a vehicle. The subset that is available by sensors of the predicting vehicle. The input parameters of the prediction are:

- velocity
- lane
- distance
- indicator lights left/right
- tail braking lights

The parameters are sufficient to recognize some of the maneuvers. The important condition is the correct usage of indicator and braking lights by other vehicles. The most important is to detect whether a vehicle is braking or changing lane and it is achieved if the condition of usage lights is satisfied. The complications can be caused by the fact that the prediction of maneuver is based only on a particular state of vehicle at the particular time. Only the first maneuver of a vehicle can be predicted like this. All the other states after the first maneuver are unsure. If the predictor is requested to provide a longer prediction the sequence of straight maneuvers is generated after the first maneuver. The example of prediction is shown in Figure 4.3

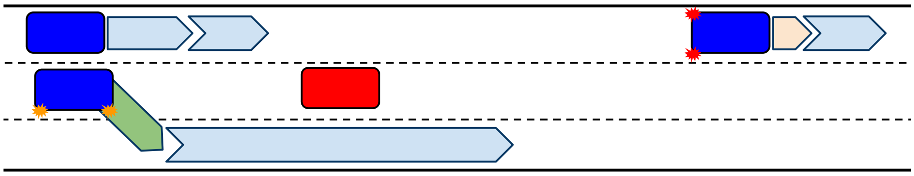

Figure 4.3: The example of prediction.

4.1.1.2 Planning

The planning is the second part of the deconfiction method. The prediction provides the set of maneuvers. The maneuvers represent the forbidden zones, where other vehicles can occur. The task of the planning part is to generate the consequence of maneuvers - the plan, while no maneuver of the plan violates the following conditions.

- The maneuver is executable on the highway, i.e. no driving out of the highway.
- The maneuver does not collide with any forbidden zone.
- The maneuver respects additional rules.

The process of creating the plan and the condition verification is explained in the following section. The example situation is shown in the Figure 4.4. The planning is simplified. The straight maneuver, turning left maneuver and turning right maneuver are considered. As is shown in the Figure 4.4 the maneuvers, that does not follow the existing highway lane are eliminated. The maneuvers colliding the forbidden zones (i.e. exists the spatial and time intersection of maneuvers) are excluded from possible plan. Applying addition rules, concerning the maneuver preferences, the optimal plan is chosen.

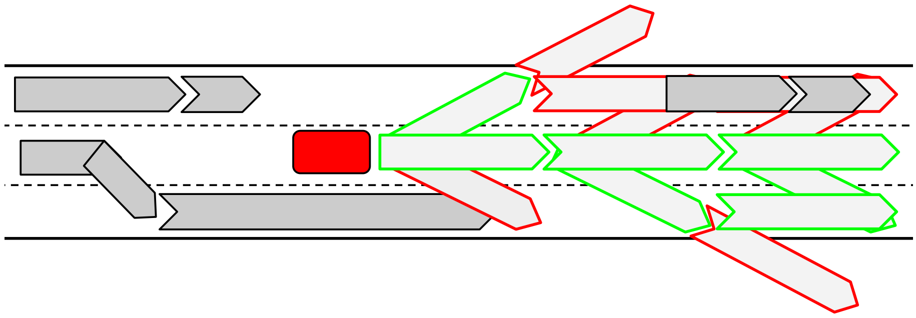

Figure 4.4: The example of the plan creation.

The non-cooperative spatial planning method is designed to correspond the cooperative methods, but with the important differences. The prediction substitutes the plan exchange between cooperating agents. Also the possible negotiation is disabled due to the missing communication in the non-cooperative scenario. The limitations of the method are following.

- The prediction is usable only for few first maneuvers. The critical time is when the maneuver predicted is unsure.
- The planning is meaningful until the critical time is reached. The length of the plan generated is limited by the critical time.
- The plan ensures the collision free drive only during the plan duration that is determined by the plan length.
- The planning does not ensure the existence of a possible plan.

Due to the limited length of plan, the planning has to be performed repeatedly. The existence of a plan is not ensured by planning but the highway situation has to be safe. Unfortunately, the plan ensures safe drive only for the plan duration. The safe situation is not ensured for the following planning process. It means that the initial safe situation can lead in an unsafe situation through the several planning periods. The further discussion about the method performance is in the Section 5.3.1.

4.2 Non-cooperative safe distance observance method

The second non-cooperative method description follows. The method is based on safe distance observance. The method compared to the planning methods (see Section 4.1) does not plan sequence of maneuvers but only one next maneuver. The simplified condition for acceptance of the maneuver is safe situation after the maneuver execution. Neither the prediction is needed, only the actual situation is taken into account.

4.2.1 Principles of the method

The method was designed to satisfy the requirements that the previous method failed to satisfy. The idea is to provide method that ensures that any vehicle cannot get from the safe state into the unsafe one. The safe state means that the vehicle is always able to perform actions preventing the collision. The reactive planning is used. A vehicle plans or makes decision about the next manuever repeatedly after the execution of the previous maneuver. The set of possible maneuvers is sorted according to preferences. The preferences are set to allow the vehicles to drive as fast as possible. The maneuvers are tested in order of preferences whether satisfy the conditions of the safe maneuver (see Section 4.2.1.1). If the maneuver satisfies all the conditions, the maneuver is chosen to be executed. The control loop is shown in the Figure 4.5.

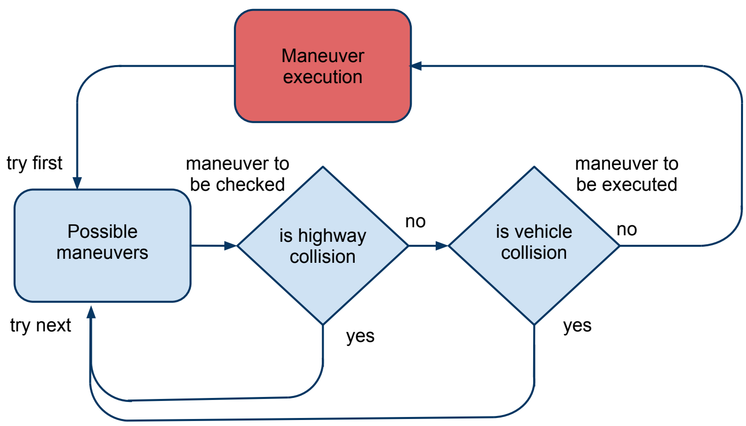

Figure 4.5: The control loop of the method.

4.2.1.1 Safe maneuver conditions

The safe maneuver is determined as the maneuver, which execution leads to a safe state. It means that there is no possible conflict, that is not solvable by a sequence of maneuvers performed by a vehicle participating in the conflict. The description of the conditions follows. The conditions correspond to the possible conflicts. The conflicts can be divided into two main groups.

- Highway collision - the highway collision is the drive out of the highway - out of the existing lanes.
- Vehicle collision

4.2.1.2 Highway collision avoidance conditions

The conditions to avoid the highway collision are following.

1. The desired lane must exist at the related highway segment.
2. The end lane of the maneuver must continue far enough to allow the vehicle to stop until the end of the lane is reached.

If the maneuver satisfies the both conditions the vehicle cannot collide with the highway. The important feature is that there is at least the deceleration maneuver that always satisfies the condition if the previous state was save. Let the first vehicle state be safe and all the following maneuvers are safe as well. The Figure 4.6 shows both example situations, with and without highway collision. The red arrows represents rejected maneuvers. The turning left maneuver fails to satisfy the condition 1. The second red arrow as a straight or acceleration maneuver is rejected due to the condition 2. On the other side the turning right and deceleration maneuver are acceptable. The pure principle of the method and initial safe state ensure the acceptability of the deceleration maneuver.

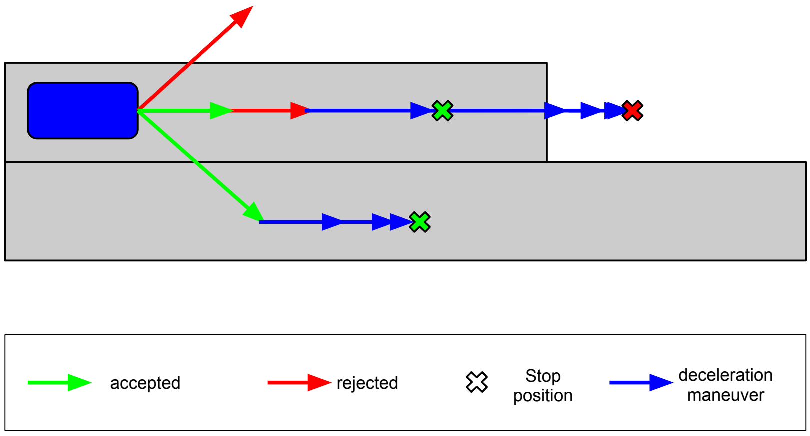

Figure 4.6: The control loop of the method

4.2.1.3 Vehicle collision avoidance conditions

The section deals with the description of conditions to avoid vehicle collision. The condition summarized into one general condition demonstrates the idea of the conditions.

- The maneuver is acceptable for a vehicle if all other vehicles that the vehicle can endanger are in safe distance from the vehicle.

The separate Section 4.2.1.4 deals with the definition and computation of the safe distance. The restriction of all vehicles to the vehicles that the vehicle can endanger has several reasons. The method is designed that the vehicle does not consider vehicles behind. The responsibility for collision avoidance has the rear vehicle. The exception is the lane change when also the vehicles behind have to be considered. Also the vehicles that are not the nearest in the particular direction can be omitted.

Let us divide the condition application into two parts. The first is the checking of the maneuvers without lane change and the second part of the maneuvers with lane change.

4.2.1.4 Safe distance check - straight maneuvers

The situation is easier if the lane is not changed (Figure 4.7). The vehicle has to check only the distance to the first vehicle ahead. The vehicle ahead then ensures the safe distance to the next vehicle ahead.

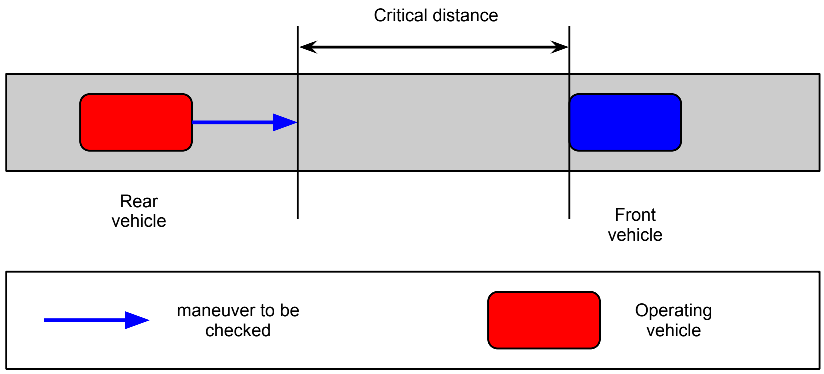

Figure 4.7: Straight maneuver safe distance check.

The important feature of the method is that it can ensure the safe state after maneuver execution. This is guaranteed because the safe distance is checked on the distance between the position after maneuver and the initial position of the vehicle ahead. And as was said before the safe state means the possible safe maneuver in the next step. Let the initial state be safe and all the future states are safe as well.

Safe distance

The knowledge of the safe distance is crucial aspect of the method. The method of computation of the safe distance is offered in this section.

The possible behaviour of a vehicle is restricted by the set of maneuvers (see Section 3.2.5.1). It allows the decision making vehicle to count with the worst possible situation that can occur. While regarding the safe distance, the worst distance is the shortest possible one. This critical distance is used to decide whether the distance between vehicles is safe. The critical distance is get as is shown in the Figure 4.7 and Figure 4.8. To decide whether the critical distance is safe we need to count the value of the minimal safe distance. The situation at time t_0 is shown in the Figure 4.7. We can use basic motion laws. The maneuvers are defined with constant acceleration a so we use it as well. The computation is based on the idea that the vehicles cannot collide if their velocities are equal.

$$v_{A1} = v_{B0}$$

$$v_{A0} + a \cdot T_S = v_{B0}$$

T_M ... maneuver duration

v_{A0} ... velocity of the rear vehicle at the end of the maneuver at $t_0 + T_M$

v_{B0} ... velocity of the front vehicle at t_0

Now we get the minimal safe braking period T_S. The minimal safe distance d_S is defined by the following equation.

$$d_S = v_{A0} \cdot T_S + \frac{1}{2} a \cdot T_S = \frac{v_{B0}^2 + v_{A0}^2}{2a}$$

The critical distance d is safe if $d > d_S + \epsilon$, where ϵ is an emergency reserve. The emergency reserve is necessary because the dimensions of the vehicles where omitted during the computation. Even the physical model responsible for vehicle movement can cause errors.

4.2.1.5 Safe distance check - lane changing maneuvers

The vehicle changing the lane has to check more vehicles whether these are in safe distance. The first the vehicle has to identify all vehicles the safe distance should be checked with. All the vehicles in the desired lane or even the vehicles changing the lane into or from the desired lane must be considered as potential danger. The closest vehicles ahead and behind are individually checked. If the decision making vehicle is the rear one, the safe distance check is identical to the check of the straight one in Figure 4.7.

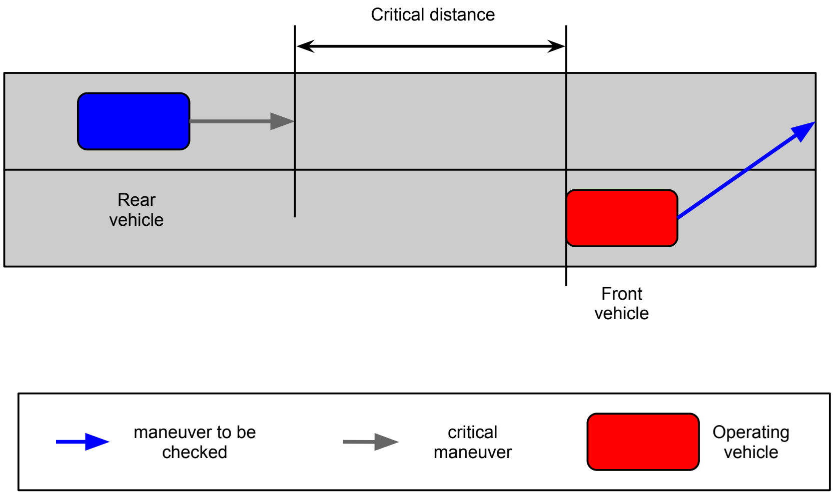

Figure 4.8: Lane change maneuver safe distance check.

If the planning vehicle has to check the distance to the vehicle behind (Figure 4.8), the process is analogical. Only the planning vehicle is the front vehicle and the second vehicle is the rear one. We do not check whether the state after the maneuver that is being checked is safe. We actually check if the vehicle behind can avoid collision with the planning vehicle even if the its current maneuver is critical - acceleration maneuver and we turn into the lane in front of it.

Chapter 5

Tests and method performance

The chapter introduces the tests of the designed and implemented methods (see the Chapter 4). The parameters and procedures of the tests are offered and described. The Section 5.2 deals with comparison of the chosen non-cooperative method with another methods of vehicle control. The method of safe distance observance, that is introduced in the Section 4.2, was chosen to represent the non-cooperative methods. The methods to compare are cooperative method [Janovský, 2011] and method based on machine learning [Franěk, 2011]. both methods are based on the same highway simulator (see Chapter 3). The Section 5.3 describes the more detailed tests of both non-cooperative methods, introduced in the Sections 4.1.1 and 4.2. The discussions of the tests are integral part of all the tests. The purpose of testing is to get relevant information about the performance of methods. The recognized features, advantages and limitations of methods are described in this chapter.

5.1 General parameters of tests

All the test are run in the highway simulator (see Chapter 3). The control methods operate in the maneuver layer. It means that the highway profile tracking is not part of the method responsibility. The lower layers are responsible for profile tracking (see Section 3.2.6). This is the reason the tests are executed on a straight highway. The simulator offers continuous creation at the beginning and removing at the end of the highway. The narrowing position is important term. The narrowing is a position on a highway where number of lanes can change. There is the only possible narrowing on a testing highway. The highway creation is because of these simplifications easily configurable by several parameters.

5.1.1 Input parameters of the tests

The input parameters of the tests correspond to the run parameters of the simulator. The required parameters are set in a configuration XML file. The parameters are displayed in the following list:

- Duration of the simulation [s]
- Highway length before narrowing [m]
- Highway length after narrowing [m]
- Number of lanes before narrowing[-]
- Number of lanes after narrowing[-]
- Minimal period of creation [s]
- Coefficient of car creation probability [-]
- Coefficient of van creation probability [-]
- Coefficient of truck creation probability [-]
- Coefficient of bus creation probability [-]

The ratio of coefficients of a vehicle type probability defines the probabilistic structure of vehicle types in the tests. There are 4 types of vehicles in the simulator, each type has defined specific parameters as maximal velocity and dimensions. The addition parameter is the seed of the simulator's random number generator. The use of the seed allows to repeat tests in the same conditions. It is used to compare the methods. The minimal period of creation is period of creation if condition that any other vehicle is not in the range of creation. The condition is the protection against collisions immediately after creation where deconfliction methods cannot react.

5.1.2 Output parameters of tests

The representable measurable parameters are chosen to be the output parameters of the tests. Several parameters are presented in the following list.

- Count of successful vehicles - vehicles that reached the end of the highway [-]
- Count of crashed vehicles [-]
- Average speed of the successful vehicles [km/h]
- Count of deceleration maneuvers executed [-]
- Count of acceleration maneuvers executed [-]
- Count of straight maneuvers executed [-]
- Count of turning right maneuvers executed [-]
- Count of turning left maneuvers executed [-]

5.2 Tests and comparison with the other methods

The tests to compare chosen non-cooperative method with cooperative one and method based on machine learning are exactly defined. The definition is consensus of the authors of all three methods. The tests were run repeatedly while various random seeds were set. The results are average values of 5 runs (seed 1-5). All the authors of the methods provided measured values. The common parameters of tests are in Table 5.1. The particular parameters of each test are part of the related Sections (5.2.2, 5.2.4, 5.2.4).

Parameter	**Value**
Duration of the simulation	600 s
Highway length before narrowing	1000 m
Highway length after narrowing	500 m
Minimal period of creation	6
Coefficient of car creation probability	5
Coefficient of van creation probability	1
Coefficient of truck creation probability	1
Coefficient of bus creation probability	1

Table 5.1: Common input parameters for tests 1-3.

5.2.1 Used control methods

The description of methods follows. The best method of the noncooperative ones, the best of the cooperative ones and the machine learning method are used.

5.2.1.1 Non-cooperative safe distance observance method

The method is described in Chapter 4 with description in section 4.2. The choice of this method is explained in Section 5.3.1.

5.2.1.2 Cooperative peer to peer method

The method is described in the [Janovský, 2011]. The basic description is offered in this section. The process of planning is well described in Figure 5.1.

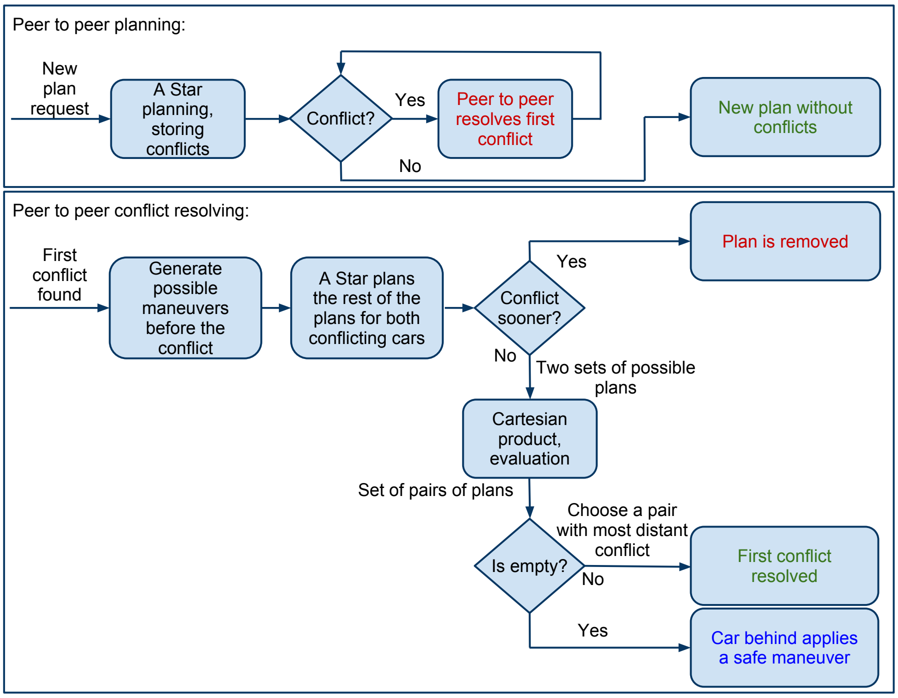

Figure 5.1: Cooperative peer to peer method diagram from [Janovský, 2011].

The method is based on planning using A* algorithm. The conflicts in plans are solved by peer to peer negotiation of vehicles. The diagram in Figure 5.1 shows more details. The concrete implementation is also described in [Janovský, 2011].

5.2.1.3 Machine learning method

The machine learning method is described in [Franěk, 2011]. The approach is different from the non-cooperative and the cooperative methods. The method is based on reinforcement learning. The each vehicle's state is defined by several parameters. A random action in particular state is performed. The actions are rewarded according to specified rules. The safe actions are the best rewarded. The actions that lead to the collision are penalised. The learning should lead to specification of the action to perform according to the temporary state.

5.2.2 Test 1

The test 1 is the easiest test due to the absence of the narrowing. The specific input parameters are in Table 5.2. The test should show the capability of methods to avoid collisions of vehicles

Parameter	**Value**
Number of lanes before narrowing	2
Number of lanes after narrowing	2

Table 5.2: Specific parameters of test 1.

Results and comments

The results in Table 5.3 are average values of tested methods from executed tests. The common test specifications are more described in Section 5.2. The parameters in the table correspond with those listed in Section 5.1.2.

Parameter	**Non-cooperative**	**Cooperative**	**Learning**
Count of successful vehicles	92.8	78.6	70.4
Count of crashed vehicles	0	0	0.4
Average speed [km/h]	112.2	84.6	68.18
Deceleration man.	51.2	250.8	431.8
Acceleration man.	1487.8	1208	1225
Straight man.	66	1209	468.2
Turning right man.	16.6	0	71.8
Turning left man.	12.2	0.4	75.2

Table 5.3: Output parameters of test 1.

The non-cooperative and cooperative methods were quite successful in collision avoidance. The machine learning method allowed in average 0.4 vehicles to crash during a test. The average speed parameter and count of successful vehicles show that non-cooperative method is capable to provide higher usage of highway capacity than the other methods. The reason of this is probably not too much limiting deconfliction by observance of the safe distance. It allows the vehicles to use the highway capacity more effectively than for example cooperative one. The cooperative one uses different method to collision recognition. And the spatial and time intersection of maneuvers, that is used to recognize conflict, is quite limiting. The cooperative method also plans for much longer distances so the straight maneuver is preferred to combination of acceleration and deceleration maneuvers. It could be the reason the non-cooperative method executes more acceleration and deceleration maneuvers.

The numbers show that machine learning use turning maneuvers more often than other two methods. The cooperative method executed almost no turning maneuvers. Possible preference of straight maneuver to turning maneuvers could even cause worse results of the average speed.

5.2.3 Test 2

Parameter	**Value**
Number of lanes before narrowing	3
Number of lanes after narrowing	2

Table 5.4: Specific parameters of test 2.

Results

The results in Table 5.3 are average values of tested methods from executed tests. The common test specifications are more described in Section 5.2. The parameters in table correspond to those listed in Section 5.1.2.

Parameter	**Non-cooperative**	**Cooperative**	**Learning**
Count of successful vehicles	86	79.2	45.2
Count of crashed vehicles	0	0	1.2
Average speed [km/h]	108	77	39.98
Deceleration man.	533.2	384.2	1060.6
Acceleration man.	1440.4	1534.4	1084.4
Straight man.	268.2	1164.2	533.6
Turning right man.	41	40.4	132.2
Turning left man.	3.8	0	117.2

Table 5.5: Output parameters of test 2.

There is narrowing from 3 to 2 lanes in this test. The number of lanes after narrowing is same as in the test 1. The test should show the impact of narrowing on the tested methods. The impact is obvious on non-cooperative and machine learning method. The cooperative method is the less impacted one. The results of cooperative method of test 1 are similar to results of the test 2. More information about narrowing and it's effect on methods is described in the following test.

5.2.4 Test 3

Parameter	**Value**
Number of lanes before narrowing	2
Number of lanes after narrowing	1

Table 5.6: Specific parameters of test 3.

Results

The results in Table 5.3 are average values of tested methods from executed tests. The common test specifications are described in more details in Section 5.2. The parameters in the table correspond to those listed in Section 5.1.2.

Parameter	**Non-cooperative**	**Cooperative**	**Learning**
Count of successful vehicles	67.6	48.2	43.4
Count of crashed vehicles	0	0.4	0
Average speed [km/h]	79.6	62	49.96
Deceleration man.	1372.6	250.8	403
Acceleration man.	1085.6	1265.4	898.8
Straight man.	1149	401	266
Turning right man.	28.2	34.4	104.2
Turning left man.	5.4	0.6	83

Table 5.7: Output parameters of test 3.

The test 3 detected the possibility of collision in cooperative method. The only collision free method during all the tests 1-3 is the non-cooperative method. But test 2 and 3 demonstrate also the weaknesses of the non-cooperative method.

Unfortunately the output parameters are not reflecting all the situation near the narrowing position. There are vehicles that are not able to get out of the not continuing lane. The vehicles are stuck before the narrowing. The problem is that if vehicles coming to the narrowing cannot change the lane (see Figure 5.2). They must slow down and they stop near the end of the lane. None of the maneuvers is applicable in this situation. The only maneuver with acceleration is the acceleration maneuver. The acceleration maneuver cannot be executed due the ending lane. The lane changing maneuver cannot be executed because the vehicle has no speed. The situation as was described is not solvable by the method.

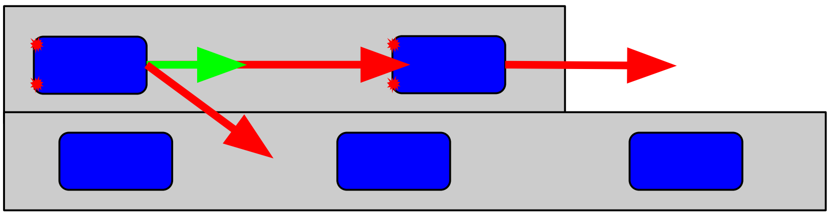

Figure 5.2: Problem of vehicles getting stuck.

5.2.5 Summary of tests

The tests showed very good results of the non-cooperative safe distance observance method. The count of vehicles that reached the end of the highway and average speed are aspects where method dominates the other compared methods. The ability of collision free drive seems to be the most valuable. The non-cooperative method is the only one that passed the tests without collision. On the other hand even the non-cooperative method's weaknesses are found. Unfortunately the output parameters of tests are not well reflecting stuck vehicles. The situation is discoverable by visual examination. The existence of possible stuck of vehicles near narrowing is the most serious problem of the method that was discovered.

Compared to the machine learning the non-cooperative method is more reliable. The specific behaviour and even the specific principle of machine learning method make the method not well predicable and comparable. The comparison with cooperative method is much more interesting. The cooperative method is the better informed method. The better results of cooperative method were expected. The average speed and number of successful vehicles is worse for non-cooperative method. It is caused by collaboration of vehicles. Simply speaking the vehicles care of each other. The non-cooperative method is globally more successful but few individual vehicles are stuck. This would make the cooperative method more acceptable. But the important aspect of collisions has to be considered as well. The absence of collisions is the great advantage of the non-cooperative method.

5.3 Non-cooperative methods tests

The section of non-cooperative tests offers tests of the not yet tested method - the planning non-cooperative method (see Section 4.1.1). it also offers more detailed testing of the safe distance observance method.

5.3.1 Spatial planning method tests

The method was described in Section 4.1.1. The description in Section 4.1.1.2 explains the reasons why the behaviour of the method is expected to be unreliable. To prove this, we use the test scenarios from Section 5.2. The conditions of the test are the same as is in the referenced tests. The safe distance method is used for comparison.

5.3.1.1 Test 1

The test 1 requires basic deconfliction - scenario without narrowing of the highway.

Parameter	**Safe distance**	**Planning**
Count of successful vehicles	92.8	85.5
Count of crashed vehicles	0	0
Average speed [km/h]	112.2	85.2

Table 5.8: Non-cooperative methods - test 1.

The both deconfliction methods are successful, no crashes are detected during test 1. The planning method achieved worse results.

5.3.1.2 Test 2

The second testing tests ability of method to solve problem of narrowing highway. In this scenario the vehicles must get from 3 lanes to 2 lanes.

Parameter	**Safe distance**	**Planning**
Count of successful vehicles	86	82.2
Count of crashed vehicles	0	0.8
Average speed [km/h]	108	93.5

Table 5.9: Non-cooperative methods - test 2.

The results of planning method are similar to the results of Safe distance method. The crucial parameter seems to be the count of crashed vehicles. The planning method is unable to perform crash free drive.

5.3.1.3 Test 3

The third test is the most difficult one. The narrowing from 2 to 1 lane is critical.

Parameter	**Safe distance**	**Planning**
Count of successful vehicles	67.6	39.8
Count of crashed vehicles	0	3.2
Average speed [km/h]	79.6	41.7

Table 5.10: Non-cooperative methods - test 3.

The planning method is not successful in the last test. The count of collisions is relatively high. The tests 2 and 3, the test with narrowing, showed the weaknesses of the planning method. Although the counts of successful vehicles using the planning method are acceptable, the crashes cause the problems.

Although the progress of the planning method's results during development was good, the perfect collision avoidance is not reached. The Section 4.1.1.2 offers some of reasons the method is unable to solve all possible conflicts. The choice of the non-cooperative method to be compared with cooperative and machine learning one is obvious due to previous section. The Safe distance method is chosen even for further testing.

5.3.2 Safe distance method tests

The elementary tests of the method are part of Section 5.2. The method showed the great potential of collision avoidance. All of the referenced elementary tests were passed without any collision. The theoretical perfect no collision drive is also expected in Section 4.2.1. So the Section 5.3.2.1 is dedicated to the collision avoidance. How the method handles the various density of traffic is topic of the Section 5.3.2.2. The only but serious insufficiency of the method are the vehicles getting stuck near the narrowing. The problem is described in Section 5.2.5. The Section 5.3.2.3 deals with the testing of the method modification that offers better narrowing passing.

5.3.2.1 Collision avoidance tests

The important feature of the safe distance method is the collision free drive. None of the previous tests detected any crash. The Table 5.11 presents the results of long-termed tests. The parameters are used the same as are described in Section 5.2, only the simulation time is prolonged.

Test	**Duration**	**Successful vehicles**	**Crashed vehicles**
Test 1	24 hours	14392	0
Test 2	24 hours	14048	0
Test 3	24 hours	7214	0

Table 5.11: Results of long-termed tests

The results indicate that the method is able to ensure the collision free drive.

5.3.2.2 Density tests

The following tests show the dependence of significant parameters on density of the highway traffic. The density of traffic is set by the minimal period of creation parameter. The values of other parameters are set according to the test 2 setting (see Section 5.2.3), only the simulation duration is prolonged to 1000 minutes.

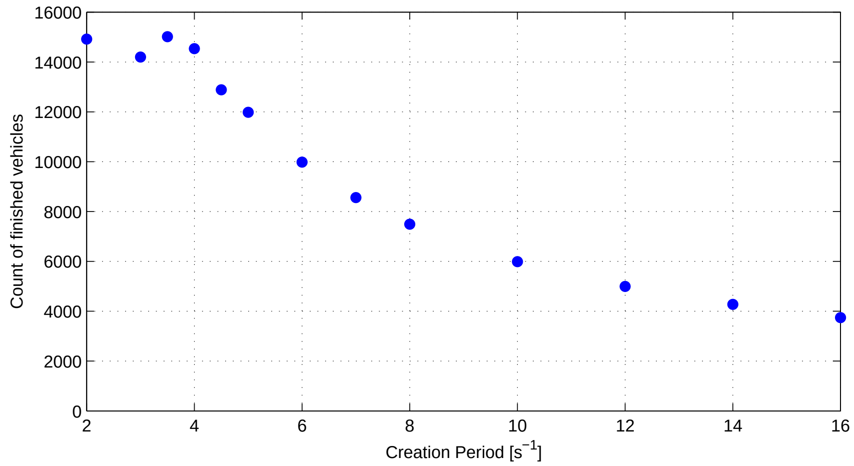

Figure 5.3: Dependence of successful cars on creation period.

The Figure 5.3 shows that the method follows the decreasing period of creation very well. The interesting situation is around the value 3.5 vehicles per second. The abnormality in figure is caused by the simulator. When the simulator creates a new vehicle, the safety range is checked. If another vehicle is not in the range, the vehicle is created. Otherwise the vehicle creation is skipped and continues after the next period. It means the method is capable to use and do not limit the majority of the simulator highway capacity.

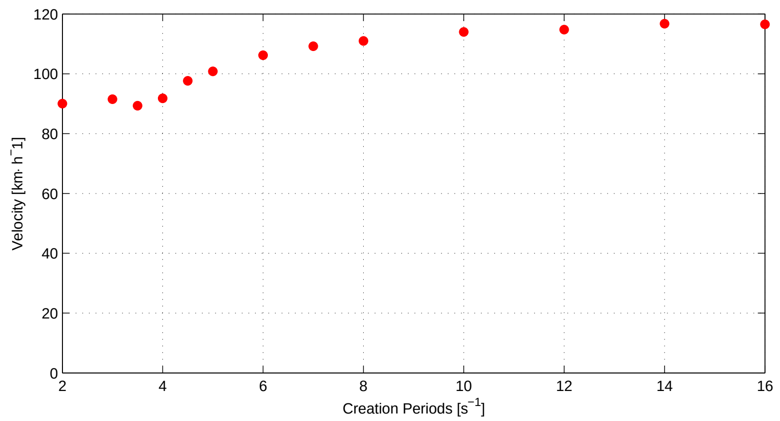

Figure 5.4: Dependence of average velocity on creation period.

The average velocity dependence on creation period is showed in Figure 5.4. The abnormality explained in previous figure is also found in this one. The average velocity is also limited by the maximal velocity of the vehicles that is obvious from the figure.

5.3.2.3 Narrowing tests

The results of previous tests showed that the safe distance method has one serious problem. The problem of vehicles getting stuck near the narrowing is mentioned in Section 5.2.4. This part of tests should outline the conditions when the vehicles tend to get stuck. The Figure 5.5 shows that the percentage of the vehicles that got stuck is increasing with the decreasing period of creation. The increase is alarming. The 10% of vehicles got stuck for the creation period 6 vehicles per second.

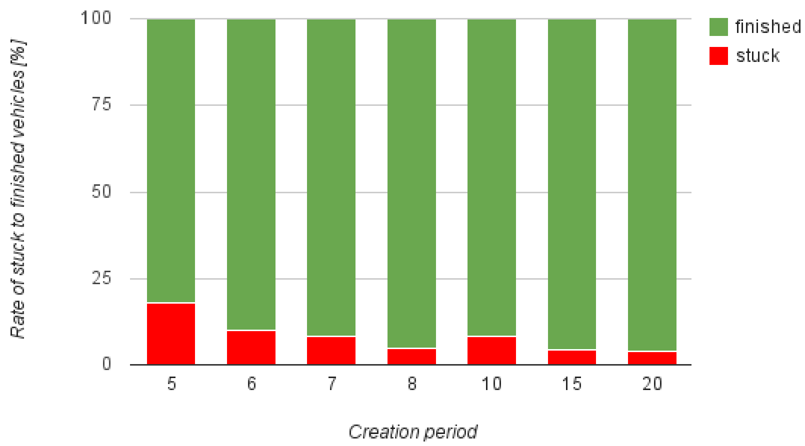

Figure 5.5: Rate of stuck to successful vehicles.

5.3.2.4 Adaptation of the method to the narrowing

The idea of the modification of the method is simple. The vehicle approaching the narrowing should change the maneuver preferences. The turning right maneuver becomes the most preferred. The second important modification changes the behaviour of vehicle in the right lane. The vehicle allows the vehicles in the ending left lane to turn to the right one. The modifications are used during so-called Narrowing mode. The principle is shown in Figure 5.6.

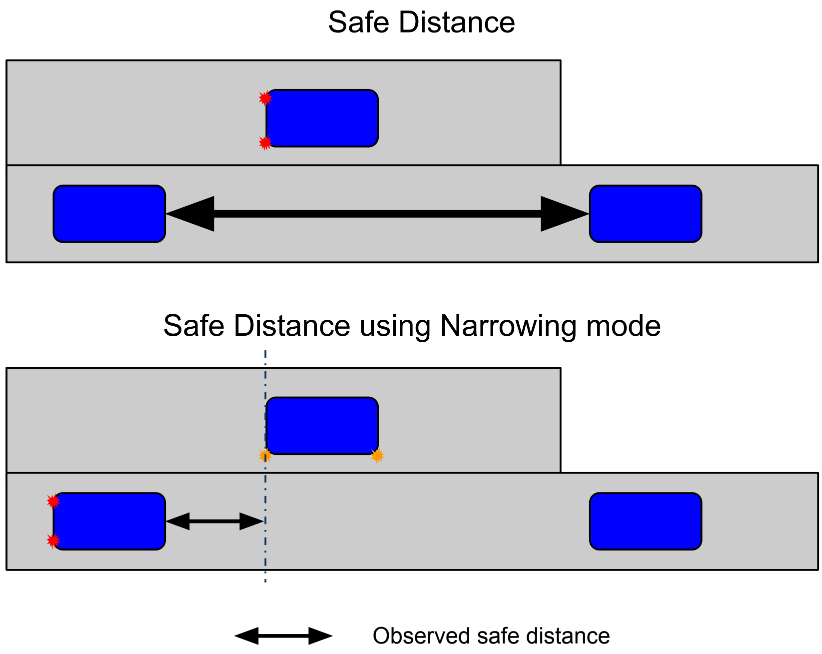

Figure 5.6: Principle of the Narrowing mode.

The conflict free drive is not affected because the modification only adds limitations. The Safe distance method using narrowing mode performance is compared to the other methods. The test 3 scenario is used. The Narrowing mode is activated 700 meters before narrowing.

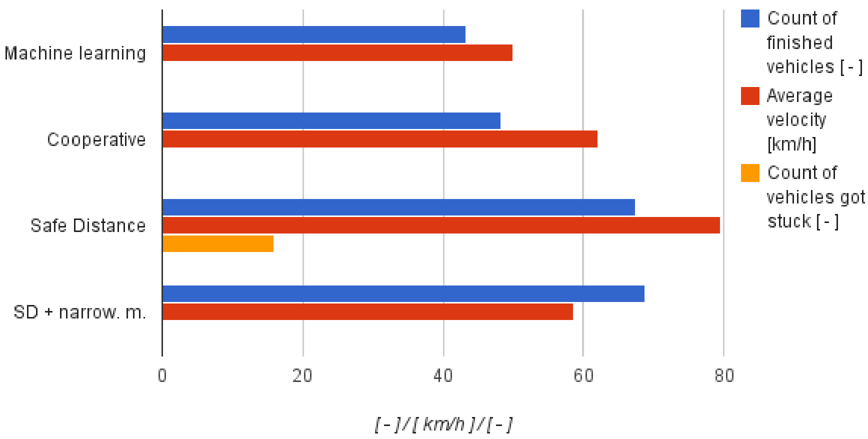

Figure 5.7: SD method using Narrowing Mode comparison with other methods.

The Figure 5.7 shows that the Narrowing mode is able to prevent the vehicles to get stuck. The prevention of getting stuck causes the reduction of the average velocity. On the other side the test shows that the count of vehicles that successfully finished the test is even higher. The Narrowing mode shows the potential to improve the Safe distance method. The introduced principles can be the bases of the further work on the Safe distance method.

Chapter 6

Conclusion

The specifics of noncooperative collision avoidance of road vehicles were introduced. Two deconfiction methods were designed and implemented. The first is the method based on spatial planning. The safe distance observance is the principle of the second method. The both methods were validated in a simulation.

The tests showed better results of the method based on the safe distance observance. The most relevant advantage of the method is the ability to avoid collisions. The tests demonstrate that the method allows to pass higher number of vehicles through highway segment than the cooperative and the machine learning methods. The vehicles getting stuck are disadvantage that makes the method less competitive. The solution of the problem is proposed. The concept of the Narrowing mode is presented. Although the Narrowing mode is not fully tested, its potential to completely eliminate the getting stuck vehicles. The potential is showed in test. The further improvement and the integration of the Narrowing mode into the safe distance method can lead to better results. The higher traffic density and flow could be reached by usage of shorter maneuvers.

The method was tested only on the highway. The application of the method out of the highway is possible topic of further work. The safe distance observance applied as a part of the complex deconfliction method is expected to be implemented. Due to the ability to ensure collision free drive, the method could be used as a supportive safety layer. For example safety layer of an advanced cooperative planning method.

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Appendix A

Source Code

The source code of the highway project is on the enclosed CD. The source codes closely related to this thesis can be found in the following directories:

- cz/agents/highway2/planner/noncooperative
- cz/agents/highway2/planner/spatialmaneuver
- cz/agents/highway2/planner/plan
- cz/agents/highway2/planner/heuristicPlanner

Appendix B

Video

The video presenting implemented method in the simulation is a part of the enclosed CD.

- videos/simulation.avi