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Multi-Agent Road Traffic Simulation : Towards Coordination by Game Theory Based Mechanism

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Abstract

Road traffic simulation is a flexible tool used for a wide variety of applications. In addition to mathematical based models, the INRETS has conducted researches based on the driver behavior. ARCHISIM is a behavioral and a multi-agent simulation model: the traffic is produced by the interaction of the agents, which are simulated drivers in virtual vehicles. Like for many agent-based applications, the coordination is a crucial issue because managing interactions is essential and proves to be complex. Simulated road traffic is an open system for which resources are limited and whose agents are competitive. Conflicts are frequent and, for some situations, agents are brought to collaborate. In this paper, we first present the behavioral traffic simulation tool ARCHISIM. We then present the coordination issue of the “traffic system” and expose the mechanisms implemented to answer ordinary and some critical traffic situations. Finally, we focus on a game theory based mechanism we are about to use to coordinate traffic at junctions in order to avoid deadlocks.

I. Traffic Simulation with ARCHISIM

Simulation modeling is an increasingly popular and effective tool for analyzing a wide variety of dynamical problems. Road traffic is an example of such problems. Different types of traffic simulation models exist [Lieberman 97]. Macroscopic models represent entities and their activities in some aggregate manner by values of density and speed. Microscopic models describe entities as individuals and the fundamental interactions take the form of mathematical formulas. All these traffic simulation models describe traffic in statistical formats.

In addition to these models, the INRETS (French National Institute for Research in Transportation and Safety) has done some research on road traffic simulation based on the driver behavior for more than ten years. The INRETS' ARCHISIM simulation tool makes use of a behavioral sub-model for driver decisions, which results from in-depth studies carried out in driving psychology [Saad 99]. In ARCHISIM, traffic phenomena come from individual actions and interactions of the various actors of the road situation [Espié 99]. ARCHISIM is a behavioral simulation model and its implementation follows the multi-agent principles; a behavioral simulation model is a multi-agent simulation model [Drogoul 93]. At INRETS, our ambition aims at making ARCHISIM an open tool for the study of the “traffic system”. Moreover, ARCHISIM has been developed such that the traffic model can host a driving simulator. In this case, the human being in the driving simulator interacts with the traffic within the simulation model. This step appears significant to us because it makes it possible to confront the new concepts with the final users while following an iterative process.

ARCHISIM is a flexible tool for which a set of applications has been found: new road design, study of test scenarios (automatic incident detection, ramp metering), etc, in fact any study relating to a modification of the “traffic system” (Figure 1).



Figure 1: Examples of traffic situations simulated with ARCHISIM

Driving is a succession of tasks, sequential or parallel, discrete or continuous. The driver perceives its environment, interpret it and tries to act consequently. Studies show that driving is a hierarchically structured activity [Michon 80] for which the concept of risk seems essential. The strategic level deals with route planning. The tactical level deals with the choice of maneuvers (lane changing...). The operational level deals with the achievement of the selected maneuver by acting on the speed and the trajectory.

Within ARCHISIM, agents are simulated drivers in virtual vehicles and consist of three subsystems: perception, interpretation and action. We focus on the “interpretation” part. Each agent has a model of its environment and interacts with the other agents (cars, trucks ...), the infrastructure (traffic lights) and the road. Each agent has goals and skills (Figure 2).

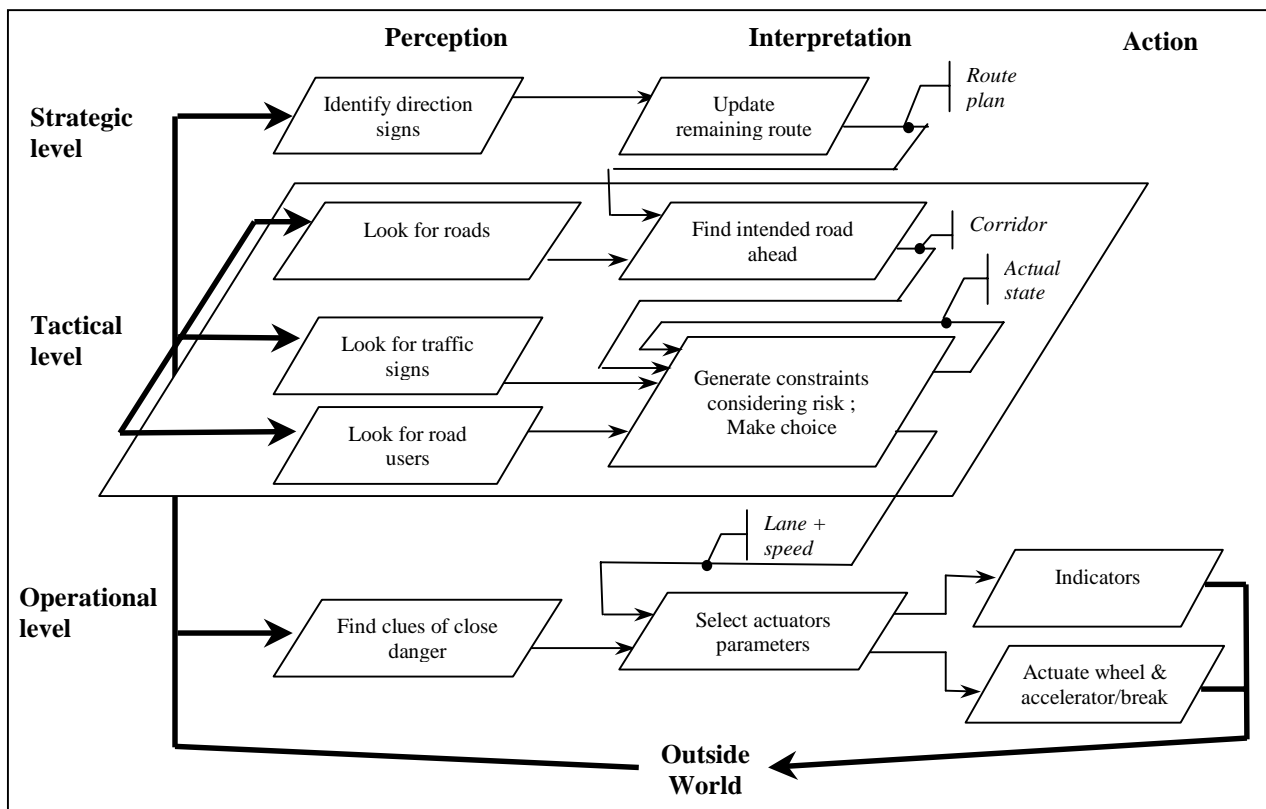


Figure 2: Partial Scheme of a simulated driver model

In opposition to works done in robotics [Reece 93], the agents' behavior is not normative. Each agent has its own attitude. The objective is not to build a robot able to drive automatically but to study the driver's behavior and the way in which the traffic phenomena occur. Within ARCHISIM, agents are autonomous and can potentially react to any situations. The system can then show a greater aptitude to organize and to coordinate itself.

In this paper, after this short presentation of the behavioral traffic simulation tool ARCHISIM, we present the coordination issue of the “traffic system”. We then expose the mechanisms implemented to answer ordinary and some critical traffic situations. Finally, we focus on a game theory based mechanism we are about to use to coordinate traffic at junctions in order to avoid deadlocks.

II. Multi-Agent Coordination and Road Traffic

Coordination is the process by which an agent reasons about its actions and the future actions of others in order to ensure the situation develops satisfactorily. The coordination of agents’ actions results from their interactions. Many definitions for coordination have been proposed [Holt 88, Malone 90]. In Distributed Artificial Intelligence, one generally agrees that coordination is managing dependencies between agents’ activities.

An activity is a set of tasks requiring resources. The categorization of the different types of dependencies between tasks and resources leads to the identification and the analysis of the coordination processes. One of the more studied coordination processes is common resource management. In this case, an effective organizational structure manages the conflicts between the agents likely to use the same resource. The coordination mechanisms that manage shared resource dependencies are resource allocation mechanisms [Steeb 81, Sathi 89]. Although the work done to formalize and generalize multi-agent coordination methods is significant [Bond 88, Jennings 96, Lesser 98], coordination mechanisms are often limited to an application. The efficiency of coordination mechanisms mainly depends on the context.

In particular, our study relates to road traffic, which is characterized by the interaction of numerous actors: road users, operators and road designers. Traffic can be considered as a supply and demand problem whose difficulty relies on two opposite postulates. The offer responds to a collective use: the road network is dimensioned to allow a certain flow. The demand is individual: each driver wishes to travel under its conditions. Therefore the “traffic system” characteristics imply strong constraints for the modeling of the agents, their interactions and the multi-agent system (Figure 3).

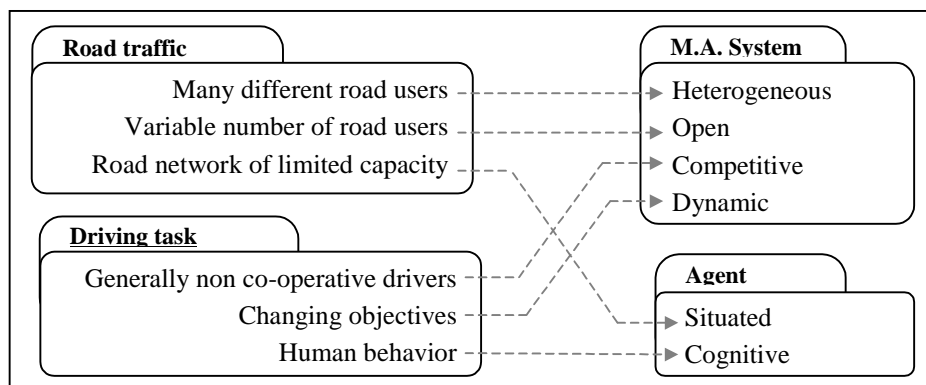


Figure 3: Characteristics of road traffic multi-agent simulation

The coordination of simulated road traffic is a distributed resources allocation problem with real-time constraint. Moreover, information perceived by the agents is geographically limited and incomplete. Also, the agents’ environment is non-deterministic and the system has an infinite number of possible states. Specific coordination mechanisms have then to be designed and developed to answer the various traffic situations.

III. Traffic Coordination Mechanisms for Behavioral Simulation

To coordinate traffic, we have considered two types of traffic situations: car-following situations, that we call ordinary situations, and situations presenting a risk of blocking, that we call critical situations. In every case, the implemented mechanisms are economic mechanisms, which are bound to the notions of profit and cost. We now present the mechanisms that are implemented for ARCHISIM to coordinate the traffic in the common situations.

III. 1. Traffic coordination for ordinary situations

Ordinary traffic situations are situations for which traffic is relatively fluid and does not show a risk of blocking. In ordinary situations, drivers' behavior results from training and is based on routine actions and reflexes [Chaib-draa 97]. In these situations, drivers generally exhibit a non-cooperative behavior and individually manage to coordinate their actions with others. Let us consider an example. Driver A has to slow down because of Driver B and is about to try to overtake it while driver C is coming from the opposite lane. There are dependencies between the drivers' activities. These activities refer to common resources that drivers have to manage with an acceptable risk (Figure 4).

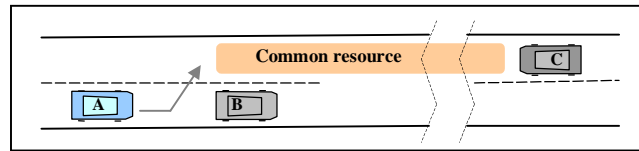


Figure 4: Example of an ordinary traffic situation

At the tactical level, the driver's objective is to determine the lane that enables to drive at a speed close to what psychologists call its "desire" speed. The driver has to consider its current state (speed, position...) and the constraints of its environment (others...) to make choices in order to satisfy its needs. A distributed resource allocation method, based on in-depth studies carried out in driving psychology and using the concepts of profit and cost, has been implemented. Each agent evaluates, for each potential target lane, the profit it can hope for and the cost –bound to the maneuver and the risk– it must support (Figure 5).

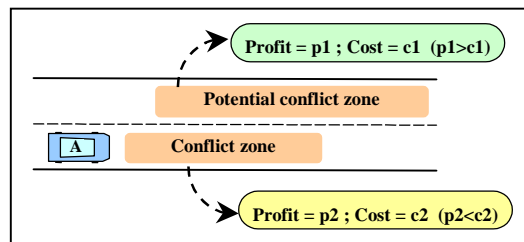


Figure 5: At the tactical level, the agent chooses a lane by using an economic model

In our example, driver A is offered two possibilities: to remain on its current lane or to overtake B. Driver A computes the profit and the cost associated with both possible lanes. For the left lane, it estimates that the cost is lower than the profit and decides to change lane.

The variables used by each agent to compute its profit and cost functions for the potential target lanes are data related to the agent's state and intentions and data referring to its close or distant environment. For an agent and a potential target lane, the *profit* mainly relates to: its "desire" speed, its current leader's speed, the distance to its current leader and the stream's speed. The *cost* is function of the risk taken for the lane changing and relates to: the effort provided for the maneuver and the stability of the traffic on the target lane.

This coordination mechanism takes into account the non-cooperative behavior of the agents. Each agent individually manages its goals and its constraints by considering the others' actions but, also, by trying to influence them. Thus, an agent can take a significant risk when overtaking and hope that the agent coming the opposite way decides to slow down.

Compared to mathematical simulation models, the mechanisms implemented for ARCHISIM are relatively costly and limit the road network loading. But, like for any emergent system, the main difficulty is finding generic rules that lead to the production of phenomena identical to the real phenomena. In spite of this, ARCHISIM has been validated for ordinary situations on highway networks [Esp   99, El Hadouaj 00, Champion 01].

III. 2. Traffic Coordination for Critical Situations

A situation is known as critical when it presents a durable risk of blocking for one or more vehicles. In such a situation, drivers, who generally have a non-cooperative behavior, are brought to collaborate. Indeed, the only obedience of the Highway Code does not make it possible to find a satisfactory solution and, while being less individualistic, drivers avoid blocking durably some vehicles. Let us consider the examples below (Figure 6).

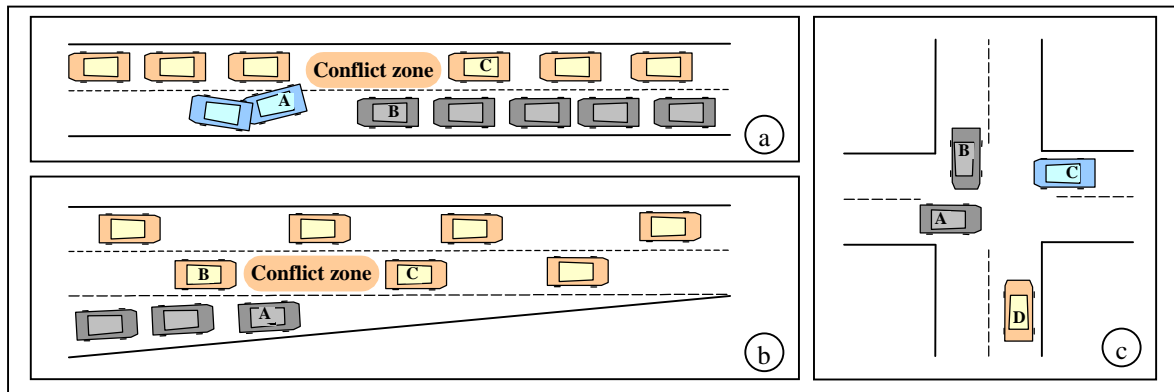


Figure 6: Examples of critical traffic situations: accident blocking a lane (a); insertion on a jammed highway (b); junction with deadlock risk (c)

In the two first examples of critical situation, the drivers understand that some of the vehicles are blocked. Then it occurs what is called the zip effect. Some vehicles on the free lane will let some blocked vehicles go. The third example stands at a junction where the drivers may block each other. At least one of the drivers decides not to enter and awaits the exit of one of the others or, a driver decides to exit although it does not have priority.

A blocking situation appears when: 1) the drivers of vehicles being on a lane that is likely to be blocked strictly follow the Highway Code and 2) the drivers of vehicles being on a lane being likely to block the vehicles on another lane have a non-cooperative behavior.

A blocking situation ends when: 1) the drivers on the blocked lane become proactive and do not follow the Highway Code any more and 2) the drivers on the blocking lane collaborate. To avoid a blocking situation, drivers adapt their behavior and collaborate.

We differentiate two classes of critical situations: the situations with flows of different priorities and situations with flows of the same priority [Champion 99]. In some situations, a flow of vehicles can be blocked by a priority flow. In some other situations, the flows have the same priority and a deadlock may appear. In critical situations with different priority flows, there is a durable risk of blocking for at least a vehicle of a non-priority flow mainly

because the priority flow has a high density. Thus, to prevent this, a priority driver may decide to collaborate and let the blocked vehicle proceed. If not, the non-priority vehicle will have to force to take a gap.

In ARCHISIM, for this type of situations, the priority agents and the non-priority agents coordinate their actions by following the procedures presented below (Figure 7). This method has been tested for accident situations, insertion situations on jammed highways and for simple T-junction situations.

Current situation	Obstacle on lane L_1 Heavy traffic on adjacent lane L_2 Current flow speed on lane L_1 : S_1 Current flow speed on adjacent lane L_2 : $S_2 \cong S_1$
Expected situation	$S_1 = 0$ for an infinite time S_2 decreasing ; $S_2 > S_1$ because lane changing expected from vehicles currently on L_1
Evaluation	Vehicles on L_1 : - gain for staying on L_1 is decreasing - cost for going to L_2 is increasing \Rightarrow lane changing more and more interesting Vehicles on L_2 : - gain for staying on L_2 is increasing - cost for going to L_1 is extremely high \Rightarrow lane changing more and more interesting
Choice	Vehicles on L_1 : slow down, try –more and more– to leave L_1 to go to L_2 Vehicles on L_2 : slow down before merge area (because of vehicles trying to come from L_1), accelerate after merge area

Figure 7: Coordination mechanism implemented for critical situations with priority flow

For deadlock situations, the problem is more complex. As drivers must anticipate the consequences of their actions and others' to avoid blocking each other, the interpretation of the whole situation is of primary importance. To try to implement this behavior with a multi-agent coordination method, we have decided to work out a game theory based method.

IV. Coordination at the Junctions: Towards a Game Theory Based Mechanism

We now expose the reasons that led us to work out a multi-agent coordination method for the traffic at the junctions. This game theory based method should solve conflicts and avoid deadlocks and livelocks.

IV. 1. The coordination issue at the junctions

What urged us to want to implement a game theory based coordination mechanism is above all that ARCHISIM, although it is validated for the motorway situations, does not allow proposing totally reliable urban network simulations. A major constraint opposes to it: some critical traffic situations at junctions can lead to deadlocks. Therefore, it is not certain that no blocking appears and immobilizes a part of the simulated traffic, what would have for consequence the non-validity of the experiment in progress.

In this context, it has been decided to revise the coordination method of the traffic at junctions. The objective is above all to implement a fast method allowing avoiding the blocking situations at junctions, even if it is made to the detriment of the realism of the local

of the simulated vehicles' behavior. Because it is the traffic as a whole that interests us first and foremost.

Research made in psychology show that any complex junction is perceived and managed by a driver as a succession of elementary crossroads: X-crossroads and T-crossroads [Saad 89]. Therefore it is possible to turn the problem to the development coordination mechanism for X-crossroads and T-crossroads. Besides, a road network in ARCHISIM is modeled by a set of such elementary crossroads.

To answer our problem, we have decided to organize our reflection in two stages. The first stage concerns the realization of a first version of the coordination mechanism, which, as it is done for the most part of the mathematical models of simulation, does not handle the conflicts inside junctions. So at first, we decide to only manage the access to junctions: as soon as a vehicle is inside a crossroad, the other vehicles potentially in conflict with it should not enter. The second stage deals with the realization of a generic version of the mechanism managing all the conflicts, including those inside junctions, therefore allowing several vehicles to simultaneously reach a junction.

The coordination mechanism has to be easily integrated into ARCHISIM. So, the idea of an economic method based on the notions of profit and cost turns out relevant. After a research made on the various types of multi-agent coordination mechanisms, we have pushed aside the planning and negotiation mechanisms because they usually are slow. We have finally opted for the idea of a game theory based mechanism, which has the advantage to be faster than the other methods.

IV. 2. Game theory and multi-agent systems

Game theory is a mathematical theory that is very widespread in the sciences for which the study of conflict situations is relevant: economics, biology, sociology, computer science...

A game, according to the common meaning, is a situation for which individuals (the players) have to choose among a certain number of possible actions in a predefined frame (the rules of the game). The result of these choices gives an exit of the game, to which is associated a positive or negative gain for each of the participants. If one disregards the idea of entertainment usually bound to the word, this definition is mathematically satisfactory. One can however add that players' interests are often different or opposite. That allows to consider the games as the simplest models of conflict situations [von Neumann 44, Duncan 85].

A game can be represented by an n -dimension table, n being the number of players. For a two-player game, every line of the table represents one of the actions player P_1 can follow, and every column represents one of player P_2 's. The table's cells correspond to a result of the game, which is a payoff vector. This representation is named strategic form or payoff matrix.

The use of the game theory to implement a multi-agent coordination mechanism was considered, probably for the first time, by Rosenschein [Rosenstein 85]. His work deals with coordination by negotiation and a certain generalization of this type of mechanism of coordination was evoked [Rosenstein 94].

Since then and over the years, the ever increasing and expanding research on Artificial Intelligence has seen the development and implementation of many commercial and industrial applications that utilize the link between agents and game theory. This ranges from highly sophisticated industrial applications, e.g. defense intelligent systems, to mail filtering and re-ordering, flight booking, selection of books etc.

Interesting work survey can be found on game theory applied to multi-agent coordination in [Khoo 95] and [Johansson 99].

In the transportation field, relatively few papers can be found about game theory based multi-agent coordination. However, some are extremely linked to our work [Kita 99].

Like most of the multi-agent coordination mechanisms, game theory based mechanisms are highly dependent on the application. This is mainly due to the strong hypotheses of the theory.

A game theory based coordination mechanism should allow to be capable of defining the players, the payoff matrix and the players' strategy, which is the process that allows the players to choose the action that seems the most interesting to them.

IV. 3. Towards coordination by game theory based mechanism

Every traffic situation being *a priori* different, the number of players at the beginning of a game is unknown. So, every agent approaching a junction should first determine who is going to play with it. This first phase of the mechanism can be complex. In the first version of the mechanism every agent considers as player all the agents coming to the same junction as it. This is not very optimal but it has the advantage to consider the problem in its wholeness.

Once the players are known, they should determine the game they are going to play. Once again, every traffic situation being *a priori* different, the game is rarely the same. A n-player game is modeled by a n-dimensional matrix and, because we are talking about driving, the possible actions are among two: to accelerate or to brake, in other words: to go or to stop. The payoff matrixes for the n-player games are 2^n -dimensional matrixes.

Let us consider the traffic situations for which two vehicles (A and B) are arriving at a junction. We notice that three types of situations can appear. Either both vehicles are not in conflict because none of them has priority ($\neg Prio(A, B)$ and $\neg Prio(B, A)$), or one of the vehicles has priority ($Prio(A, B)$ and $\neg Prio(B, A)$), or both vehicles have priority ($Prio(A, B)$ and $Prio(B, A)$) (Figure 8).

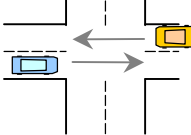
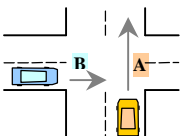
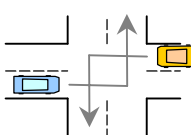
	$\neg Prio(A, B)$ and $\neg Prio(B, A)$:		
	$A \setminus B$	Go	Stop
	Go	(100, 100) *	(100, 0)
	Stop	(0, 100)	(0, 0)
	$Prio(A, B)$ and $\neg Prio(B, A)$:		
	$A \setminus B$	Go	Stop
	Go	(-50, -100)	(100, 0) *
	Stop	(0, 50)	(0, 0)
	$Prio(A, B)$ and $Prio(B, A)$:		
	$A \setminus B$	Go	Stop
	Go	(-50, -50)	(50, 0) *
	Stop	(0, 50) *	(0, 0)

Figure 8: Payoff matrix for each of the three types of situation implying two vehicles

Three types of games exist. Therefore, there are three different payoff matrixes for the two-player games. The values of the payoffs were determined according to the notions of priority and responsibility. Hence, a priority vehicle should reach the junction before a non-priority vehicle and, if a non-priority vehicle reaches the first the junction, it is considered as

responsible in the event of an accident. Consequently, it seems logical: to give a more important profit (100) to a priority vehicle than to a vehicle that is not (50); to give a weaker cost (50) to a priority vehicle than to a vehicle that is not (100) when both reach simultaneously a junction; and finally to give an nil payoff to any vehicle staying outside the junction. Naturally, these values are examples; it is only necessary to remember the ratio.

Let us now consider the resolving of the game, that is to say the strategy that every player is going to take. Every player should choose between both possible actions: *go* and *stop*. For that purpose, it calculates the average payoff associated to each of these actions by doing an arithmetical mean. One notices that in the situation for which both vehicles have priority, two strategies can be chosen: one or the other vehicle moves (Figure 8). This shows that the players are indecisive: there is a risk of blocking.

So that there is coordination, it is necessary the traffic to be coherent. Therefore the players should choose their strategy so that the resolving of the game leads to a unique ending. In case several endings equal –that is when a deadlock is possible–, it is necessary to set up a method leading to the choice of a single ending. To do so, we have simulated the fact that in such a situation, the traffic rules foresee that the driver who possesses the oldest driving license should go first. Hence, a number is assigned to every player in consideration of its age in the simulation. Then the payoff matrix is computed again: for the action *go*, a player adds the number of the other and subtracts his; for the action *stop*, he adds his number and subtracts the other's (Figure 9).

Prio(A,B) and Prio(B,A) :			A is the oldest : A is player #1 and player B is player #2			
$A \setminus B$	Go	Stop	\rightarrow	$A \setminus B$	Go	Stop
Go	$(-50+2-1, -50+1-2)$	$(50+2-1, 0+2-1)$		Go	$(-49, -51)$	$(51, 1)^*$
Stop	$(0+1-2, 50+1-2)$	$(0+1-2, 0+2-1)$		Stop	$(-1, 49)$	$(-1, 1)$

Figure 9: Consideration of the players' number when several ending are possible

A mechanism allowing the coordination of n vehicles is henceforth possible. Let us take as hypothesis of reflection that an n-player game (an n-dimensional matrix) can be represented by $(n^2-n)÷2$ two-player games. The problem is then to do the aggregation of the two-dimensional matrixes whose cells are two-value vectors into an n-dimensional unique matrix whose cells are n-value vectors. The aggregation method that has been chosen is the sum the payoffs and the formula for the three-player game is presented below (Formula 1).

$$\begin{aligned}
&\forall P = (\text{player1}, \text{player2}, \text{player3}) : \text{set of the three players of the game} \\
&\forall a \in P ; \forall b \in P - a ; \forall c \in P - a - b \\
&\forall S_a, S_b \text{ and } S_c \in (\text{Go}, \text{Stop}) : \text{possible strategies of the players} \\
&\forall M_{ab}, M_{bc}, M_{ac} : \text{matrixes of the 2-player games} \\
&\forall M_{abc} : \text{matrix of the 3-player game} \\
&M_{abc}(S_a, S_b, S_c)^a = M_{ab}(S_a, S_b)^a + M_{ac}(S_a, S_c)^a \\
&\text{with } M_{abc}(S_a, S_b, S_c)^a : \text{payoff for player } a \text{ and strategy } (S_a, S_b, S_c)
\end{aligned}$$

Formula 1: Calculation of a 3-player game matrix by aggregating the three 2-player game matrixes.

We now present the example of a traffic situation for which three vehicles are approaching a junction (Figure 10). It is about a three-player game for which it is necessary to determine three-dimensional matrix from the three two-player game matrixes. The resolving of the game indicates that its solution is *(stop, go, stop)*: only the second player (*B*) enters the junction. In this example, player *A*'s strategy is indecisive because the sums of the payoffs associated to each of both possible strategies are equal (they are worth 0). In that case, no strategy is better than the other is and the one to be chosen is the most careful: *stop*.

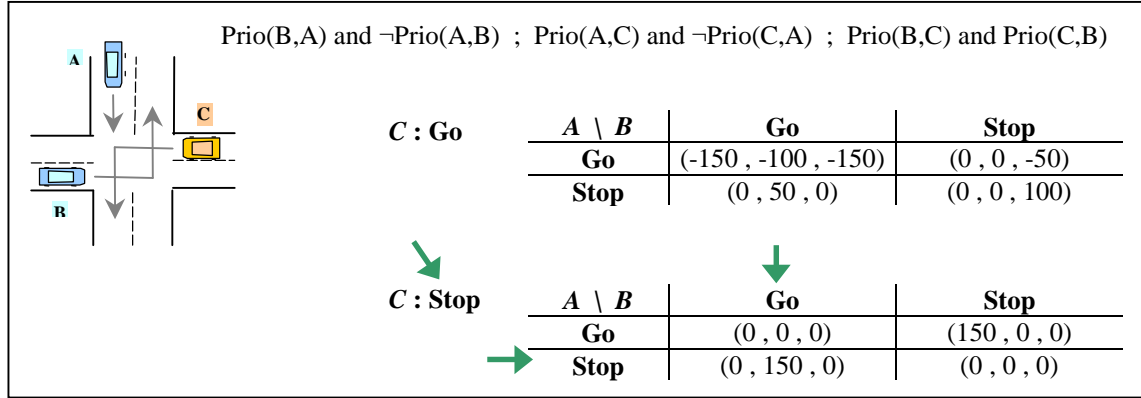


Figure 10: For a three-player game, calculation of the matrix from the three two-player game matrixes

A game theory based multi-agent coordination mechanism, dedicated to the coordination of simulated road traffic at junctions, was proposed. It seems relevant for the situations involving three agents. Tests are in progress to empirically verify its validity whatever the situations are. The generalization of this first version of the mechanism for the situations involving n agents and the generic version of the mechanism allowing the coordination of the traffic inside the junctions are also in progress.

V. Conclusion

Simulated road traffic is a phenomenon produced from the coordination of a heterogeneous, open, dynamic and competitive system, composed of autonomous cognitive agents. We showed that in behavioral simulation the coordination of the system is a distributed resource allocation issue with a real-time constraint. The mechanisms implemented in ARCHISIM to solve ordinary situations of traffic were exposed. They are mainly based on an economic approach and have allowed the validation of ARCHISIM for ordinary situations on highway network.

For critical traffic situations, such as junctions, the issue is more complex because deadlocks may occur. To coordinate the agents' actions at the junctions, we have implemented a game theory based mechanism. A first version of this mechanism, which solve the conflicts by letting agents reach the junction one by one, was presented. This mechanism works for two-player game and tests for n -player games are in progress.

Currently, we are also working on a generic version of the mechanism. Like for any mechanism utilizing game theory, some limitations may appear. So, besides the fact that all the agents should have the knowledge of the payoff matrix and consequently the preferences of all the players, they must also be homogeneous, i.e. to have initially fixed identical characteristics and capacities. These limitations are for the greater part inherent to the game theory and any mechanism based on this theory should take them into account. For behavioral road traffic simulation, we should remind that the driver does not have a normative behavior and the notion of rationality has to be defined in the context of the driving task. Indeed, in

some situations the driver presents a rather individualistic behavior and generally tries to maximize his route, while in some critical situations he is brought to collaborate. Furthermore, even if a driver model may be defined, every driver is different.

For all these reasons, this is why –at the moment– we consider our future generic mechanism more like a game theory based mechanism than a game theoretic mechanism. While the generic version of the mechanism is not defined, we consider that game theory is, in our context, more like a tool for reflection than a solution by itself.

Acknowledgement

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