Holonification of Road Traffic based on Graph Theory

Igor Tchappi Haman[1 2], Stéphane Galland[1], Vivient Corneille Kamla[3], and Jean Claude Kamgang[3]

[1] LE2I, Univ. Bourgogne Franche-Comté, UTBM, F-90010 Belfort, France
firstname.lastname@utbm.fr
[2] Faculty of Sciences, University of Ngaoundere, Ngaoundere, BP : 454, Cameroon
[3] ENSAI, University of Ngaoundere, Ngaoundere, BP : 454, Cameroon

Abstract. Organizational models and holonic multi-agent systems are growing as a powerful tool for modeling and developing large-scale complex system. The main issue in deploying holonic multiagent systems is the building of the holonic model called holarchy. This paper presents a novel top down approach based on graph theory in order to build recursively the initial holarchy of road traffic. Moreover, multilevel indicators based on standard deviation is proposed in order to evaluate the consistency of the holonification process.

Keywords: Graph theory; Holonic Multiagent System; Road Traffic; Multilevel Model

1 Introduction

In the last decades, there has been several research on agent organization in Multi-Agent System (MAS) field. Organizational approach could improve the overall performance and effectiveness of multi-agent systems and allows to model successfully complex systems [10] by defining several abstractions levels of system. Road traffic is a complex system because interactions between vehicles are non-linear, the collective behavior of vehicles is non-trivial and traffic exhibits hierarchical self-organization behavior under selective constraints. Modeling and simulation of traffic is one of the effective solution in order to understand the relationship between abstraction level exhibited by traffic and to manage and improve traffic flow. Three main approaches are presented to model road traffic in literature [13]: microscopic, intermediate (mesoscopic and hybrid or multilevel) and macroscopic approach. Macroscopic level requires a high number of entities and generally is applied on highway while microscopic level requires a high computational cost and generally is applied on small urban area scale with a high degree of accuracy. Both of macroscopic and microscopic models are not suitable to deal with large scale traffic, particularly in developing countries where there is a few cluster to well computes microscopic model and there is a few highway to well apply macroscopic models. To model and simulate large scale road traffic in these countries, we argue that an intermediate approach like mesoscopic or multilevel is needed. Multilevel [17] [15] or hybrid model integrates different representations in the same model (micro-meso, meso-macro, micro-macro) with the advantages of the models integrated. This motivation leads the paper to focus on multilevel modeling of large scale road traffic.

The principle generally applied in modeling of multilevel model is to divide the road network into several part. Each part of road traffic is associated to an abstraction level. The goal of hybridization is therefore to deals with the transition between the different abstraction levels at the border [3]. Consequently, most of the existing hybrid models are static and define a priori the different abstraction levels [20]. However, to be able to observe congestion formation or to find the exact location of a jam in a macro section, a dynamic hybrid modeling approach is needed [2]. There are a very few works dedicated to the dynamic multilevel of traffic flow [2]. The paper takes a step towards a dynamic multilevel agent-based model throw holonic multiagent system (HMAS).

HMAS have been studied on various large-scale applications successfully and holonic organizations are among the successful organizational models that have been introduced in multi-agent systems [11]. HMAS allows to dynamically switch between level of detail according to simulation objectives or computational resources [10]. HMAS is a recursive structure of holons. A holon is a natural or artificial structure that is stable and coherent and that consists of several holons as sub-structures.

In general, the life-cycle of HMAS consists of two primary stages: *building the initial holarchy* and controlling its structure against internal and external stimuli during its lifetime [7]. The initial holarchy represents the system structure in term of composition at time $t = 0$ while control structure of system against internal and external stimuli represents the life of system structure at time $t > 0$. The contribution of this paper is on ***building the initial holarchy*** of large-scale road traffic descending manner using a graph for supporting the decomposition process. To this end, paper considers road traffic as a recursive system and presents the recursive decomposition of traffic.

The paper presents a holonification method based on graph theory. Graph theory is used to model and solving various problems [1] and contains many well established algorithms like graph bisection. In the proposed method, vehicles are represented by the graph's vertices and the follower $\rightarrow$ leader relationship by the graph's edges. The method is top down recursive decomposition of the graph in order to build holarchy of road traffic. A validation of our multilevel approach is based on a standard deviation indicators.

The rest of this paper is organized as follows: in section 2, paper presents a brief description of holonic multi-agent system and related works. Section 3 explains our graph-based holonification road traffic algorithm in detail. Experimentation and results is presented in section 4. Finally, section 5 gives a conclusion and future works.

2 Related works and holonic multi-agent systems

Holonic modeling is used to model the intrinsic hierarchical nature of the systems. Holonic organizations strengths are modularity, multiple architectures, heterogeneity of languages and application safety [8]. A holon, according to Arthur Koestler [14] is defined as simultaneously a whole and a part of the whole, thus it can be made up of other holons, strictly meeting three conditions: being stable, having a capacity for autonomy and being able to cooperate. One of the most interesting properties of holonic systems, which is the essence of their complexity, is that a holon can be both an entity and an organization. The holons are therefore stable and self-similar or recursive structures. The hierarchic structure of HMAS allows to simulate system at several abstraction level according to simulation objectives or computational resources. A holarchy is shown on Fig. 1. HMAS can allows to switch into different level of holarchy dynamically [10].

As stated before, the life-cycle of HMAS consist of two stages: building the initial holarchy (holonification) and control the system structure over time. The initial holarchy of HMAS depicts the overall composition of all holons at each abstraction level at time $t = 0$. The control structure against internal and external stimuli depicts the self-organization of HMAS over time.

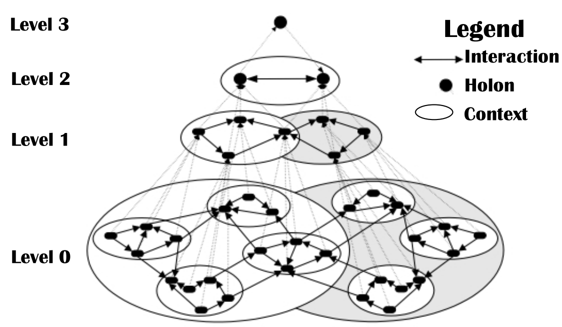

Fig. 1. A nested holarchy of four holarchical level

The Role-Interaction-Organization (RIO) model [12] is one of the models to design holonic multiagent system. The RIO concepts are:

- Organization: A set of roles and their interactions pattern define an organization in a specific domain. The concept of organization combines roles and their interactions.
- Role: A role is the abstraction of a behavior in a certain context and confers a status within the organization. Roles may interact with other roles defined in the same organization. There are predefined roles named holonic

roles. Among the holonic roles [19], there are `Head`, `StandAlone`, `Part` and `Multipart` role.
– Interaction: An interaction links two roles in a way that an action in the first role produces a reaction in the second.

Among the works on building the initial holarchy of multiagent system, Esmaeili et al. [6] proposed a method, inspired from social networks, to build the initial holonic structures of multi-agent network with a bottom-up approach. The prerequisite of their method is an un-weighted undirected multi-agent network model. They use urban traffic signal control to evaluate the quality of the holons constructed. The main limit of this work is they assume that importance of their agents is based on eigenvector centrality in social networks. In fact, this assumption is restrictive and not compatible with several complex system.

Abdoos et al. [1] has proposed a method to construct the initial holarchy for a multi-agent urban area network based on graph theory in order to recognize and form the holons. In their method, agents are modeled using an undirected and weighted graph which the weights denote the degrees of the dependencies between the agents. In order to evaluate the consistency of their method, authors propose a quality measure based on the dependencies between the agents. Their approach is bottom-up and seems to be general. However the main drawback of this algorithm is the reformation of graph after each choice of best candidates to form a holon or to join an existing holon which increases computational cost. Another shortcoming is that they build only the first level of holarchy. Our approach can build more than one hierarchical levels.

A graph G is a pair of sets $G = (V, E)$. The set V is the set of vertices and the set E contains the edges of the graph. The partitioning problem is defined as follows: given a graph $G = (V, E)$, partition V into subsets such that (1) no subset is empty, (2) the union of subsets is equal to V, (3) all the subsets are disjoint two by two. Bisection is the partition of graph in two subsets. In application, in general, bisection of graph is recursive that's means first partition the graph in two partitions, then partition each of these two partitions in two sub-partitions and so on. For some important classes of graphs, recursive bisection works quite well and if the goal does not insist on partitions of exactly equal size, it is possible to use recursive bisection to find good partitions [5]. Holonification is very similar to the concept of partitioning in graph theory [1].

3 Proposed model

In highway or urban areas, sometimes vehicles follow one another on a line and tend to regroup in convoys when approaching a heavy vehicle or when the road becomes winding [21]. These groups of spontaneous vehicles is called convoy in this paper. Whenever a spontaneous grouping of entities is possible organizational and holonic approach is interesting [20]. The formation of groups of vehicles is a problem of self-organization known as clustering or partitioning and it applied in many traffic areas such traffic control [1], and vehicular network [21]. The partitioning approaches are well adapted to road traffic because the dynamics of road traffic triggers the formation of "natural" clusters at the intersections, or convoys on the highway. [21].

Vèque et al. [21] assert that "the geographical position of vehicles is one of the important criteria in clustering". In the same paper, they also assert that: "since vehicles move in a space constrained by routes, other criteria are also significant such as speed and direction". According tho these assertions, in our model the criterion used to model vehicles are speed, position, length of vehicle and direction (lane).

3.1 Organizational model of road traffic

One approach concerning the design of multilevel agent based model is to observe, detect and possibly reify (or more precisely agentity) phenomena emerging from agents interactions [16]. According to this assertion, in order to build our multilevel road traffic model, we can observe the emergent phenomena in traffic and reify it. In traffic simulation, congestion (the queue of tighter vehicles) is an emergent phenomenon due to the interaction between vehicles. In this paper, the queue of tighter vehicles is called convoy. Fig 2 presents the organizational model of road traffic. There a three organizations: Vehicles plays role `Vehicle`

- `Organization Free Driver`: In this organization one role is defined: the role `Free`. This role is played by an agent which goes to its desired speed.
- `Organization Car Following`: In this organization two roles are defined: the role `Leader` and the `Follower`. The `Leader` is the vehicle located just in front of the `Follower` or the `Follower` is the vehicle located just behind the `Leader`.
- `Organization Convoy`: In this organization two roles are defined: the role `Head` and the `Member`. The agent which plays role `Head` is the vehicle on the top of convoy; the others agents vehicles which belongs to a convoy play role `Members`. The `Head` role is the representative of the convoy and imposes his speed to all the convoy.

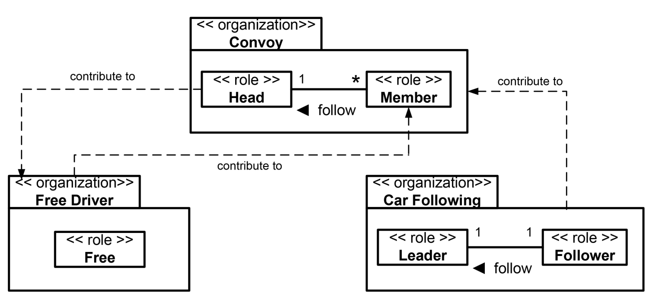

Fig. 2. Road traffic organizational model according to the ASPECS [4] methodology's formalism

An organization is made up of organizations, so we can recursively define road traffic organization as follows:
$Organization ::=< Convoys, Free\_Drivers >$
$Convoys ::= \{Convoy\}$
$Convoy ::=< Head, Members >$
$Members ::= \{Car\_Following\}$
$Car\_Following ::=< Leader, Follower >$
$Free\_Drivers ::= \{Free\}$
$Free ::=< Agent >$
$Leader ::=< Agent >$
$Follower ::=< Agent >$
$Agent ::=< Vehicle, Driver >$

3.2 Holonic model of road traffic

In order to represent car following interaction among vehicles, concepts of graph theory is useful to model relationships and interactions in complex systems. In this paper, a directed and weighted graph is used in which, the agents (couple vehicle–driver) are represented by the vertices. A directed edge represent the car following interaction among two vehicles (a follower and a leader). Road traffic can be represented by a graph as in Eq. 1.

$$G = ((V, E),\ \mathcal{W}_E, \mathcal{W}_V),\ \mathcal{W}_E : E \to \mathbb{R}_+,\ \mathcal{W}_V : V \to \mathbb{R}_+^4 \tag{1}$$

V represents the set of vertices (vehicles); E represents the set of edges (car following interactions among follower and leader); $\mathcal{W}_E$ is the weight of edges (inter-distances between leader and follower); and $\mathcal{W}_V$ is the weight of vertices (features of vehicles).
$\forall v \in \mathcal{W}_V, \quad \mathcal{W}_V(v) = (x, y, l, L)$, x is position, y is speed, l is length and L is lane where agent vehicle moves.
$\forall e = (v_1, v_2) \in E$, v_2 is the leader of v_1 or v_1 is the follower of v_2. The weight of each edge is inter-distance between vehicles and is given by Eq. 2.

$$\forall e = (v_1, v_2) \in E, \mathcal{W}_E(e) = x(v_2) - x(v_1) - l(v_2) \tag{2}$$

Numerous approaches exist depending on the problem to partition a graph. If the geometric layout of the graph is known, an appropriate recursive bisection could be used [5]. In our case, we have the geometric information about the road traffic graph, consequently, application of recursive bisection in order to build the top-down holarchy of traffic is possible. Fig 3 and Fig 4 present an example of geometric layout of traffic with two lanes and a few vehicles and his corresponding graph according to our method. In this example, $G = (V, E)$ such that $V = (v_1, v_2, v_3, v_4, v_5, v_6, v_7, v_8, v_9, v_{10}, v_{11}, v_{12})$ and
$E = ((v_1, v_2), (v_2, v_3), (v_3, v_4), (v_4, v_5), (v_5, v_6), (v_6, v_7), (v_7, v_8), (v_9, v_{10}), (v_{10}, v_{11}), (v_{11}, v_{12}))$.

The road traffic graph have the following properties:

- simple directed graph (oriented and without loops or multiple edges),

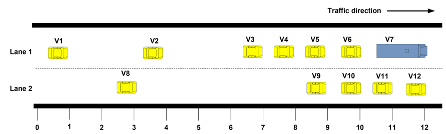

Fig. 3. A traffic situation

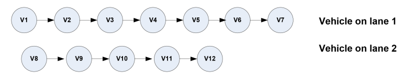

Fig. 4. Corresponding traffic graph

– planar graph (can draw in a plane without crossing two edges),
– acyclic graph (graph without cycle)

Let be $G_1 = (V_1, E_1),\ G_2 = (V_2, E_2)$ two partitions of G. A cut is a partition of the vertices of a graph into two disjoint subsets. A cut [5] of G is defined by Eq. 3.

$$cut(G_1, G_2) = \sum_{v_1 \in V_1, v_2 \in V_2} \mathcal{W}_E(v_1, v_2) \tag{3}$$

3.3 Holon formation

The holonic model of complex system partitions and hierarchizes agents into group or holons in such that the most related group of agents belong to the same holon. The proposed holonification algorithm to extract the holarchy for a given graph $G =< V, E, \mathcal{W}_V, \mathcal{W}_E >$, is given by Algorithm 1. In this algorithm, vehicles are vertices and interactions follower $\rightarrow$ leader between vehicles are edges. Algorithm 1 begins with a graph of the set of agents' vehicles with their own internal state described by four variables characteristics: speed, length, position and lane. The algorithm starts at level 0 with an empty set of holons and build the upper level (the holarchy). Decomposition of graph is based on bisection of graph on the edge with a maximum weight (line 7) if graph is connected (road traffic on a single lane). Nevertheless, If graph is not connected (road traffic on several lanes), the recursive bisection will firstly make a connected graph (line 9) in order to work on a single lane. During a recursive bisection of graph, new holons are created at each abstraction level. We have assumed that holons can't overlap i.e. at each abstraction level, holons are disjoints.

3.4 Multilevel indicators

The holonic model reduces the complexity of system and occurs to model and simulate large scale system. Holons with complex objectives are decomposed into sub-holons such that holon behavior approximates the behavior of his sub-holons. To this end, the behavior of a holon is obtained by finding the mean of the behavior (mean of speed, unweighted barycenter of position) of his sub-holons.

Multilevel indicators helps to ensure the consistency of the decomposition process. In other words, multilevel indicators helps to ensure that an aggregated behavior of a given holon is an acceptable approximation of his holons members.

Algorithm 1 Extract all the holarchy

procedure HOLARCHY($G = (V, E)$)
    Create an empty holon H at level *level*
    $H^{level} \leftarrow V$
    if $|V| \geq 2$ **then**
        for each $e \in E$, compute $\mathcal{W}_E(e)$ as in Eq. 2
        if G is a connected graph **then**
            $G_1, G_2 = maxCut(G)$ ▷ On the maximum edge weight as in Eq 3
        else
            $G_1, G_2 = minCut(G)$ ▷ On the minimum edge weight as in Eq 3
        end if
        HOLARCHY($G_1 = (V_1, E_1), \epsilon_1, \epsilon_2, level + 1$)
        HOLARCHY($G_2 = (V_2, E_2), \epsilon_1, \epsilon_2, level + 1$)
    else
        HOLARCHY($G = (V, E), \epsilon_1, \epsilon_2, level + 1$) if abstraction level $level + 1$ exist ▷ Stopping condition
    end if
end procedure

In order to ensure the consistency of a holon approximation from his holons members, the papers focus on standard deviation. Standard deviation is a statistical concept used to measure the dispersion of a dataset. This paper uses standard deviation to measure the dispersion of a set of vehicles inter-distance and the dispersion of a set of vehicles speed.

Eq. (4) measures the dispersion of a set of vehicles inter-distance.

$$\sigma_{\mathcal{W}_E} = \sqrt{\frac{1}{|E|} \sum_{e \in E} (\mathcal{W}_E(e) - \overline{\mathcal{W}_E(e)})^2} \quad \text{where} \quad \overline{\mathcal{W}_E} = \frac{1}{|E|} \sum_{e \in E} (\mathcal{W}_E(e)) \tag{4}$$

Eq. (5) measures the dispersion of a set of vehicles speed.

$$\sigma_{y(V)} = \sqrt{\frac{1}{|V|} \sum_{v \in V} (y(v) - \overline{y(V)})^2} \quad \text{where} \quad \overline{y(V)} = \frac{1}{|V|} \sum_{v \in V} y(v) \tag{5}$$

3.5 Case study

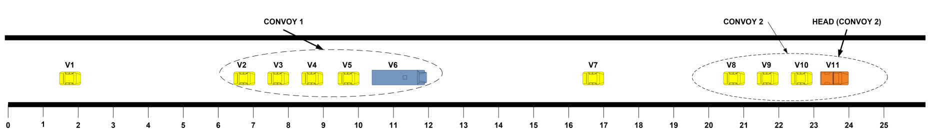

Fig. 5. A snapshot Example

	v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}	v_{11}
X (position)	2	7	8	9	10	12	17	21	22	23	24
Y (velocity)	45.0	20.1	20.5	20.3	19.9	20.8	40.0	31.1	31.5	31.2	31.7

Table 1. Pair (position, velocity) of each vehicle in snapshot

Generally, in traffic simulation, vehicles are generated and distributed on a road network throw an Origin/Destination matrix. Let Fig 5 represents vehicles on a lane at time $t = 0$ of the system life. The initial characteristics of vehicles are recorded in the table 1. For case study simplification, all vehicles are on a same lane and we don't consider length of vehicle (vehicles are like points). Application of our recursive bisection algorithm give the holarchy shown in Fig 6.

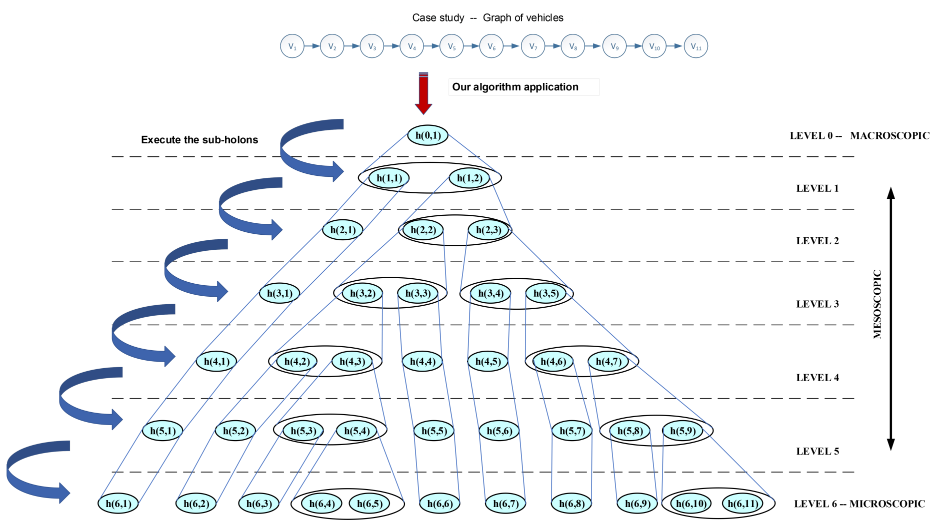

Fig. 6. Application of algorithm on example

Holons composition are given by Table 2. As the standard deviation of a group consisting of a single member is zero, we did not insert these values in order to not saturate the Table 2.

3.6 Discussion

Several abstraction levels are considered for the `Vehicle` role. The more precise level corresponds to the microscopic level (level 6 in the case study): a vehicle is associated with a holon. At the upper level called macroscopic (level 0 of case study), the behavior of the super-holon approximates a group of vehicles.

Level	Holons	Standard deviation (inter-distance)	Standard deviation (speed)
0	$h(0,1) = \{v_1, v_2, v_3, v_4, v_5, v_6, v_7, v_8, v_9, v_{10}, v_{11}\}$	$\sigma_x^{h(0,1)} = 1.66$	$\sigma_y^{h(0,1)} = 8.38$
1	$h(1,1) = \{v_1\}$; $h(1,2) = \{v_2, v_3, v_4, v_5, v_6, v_7, v_8, v_9, v_{10}, v_{11}\}$	$\sigma_x^{h(1,2)} = 1.44$	$\sigma_y^{h(1,2)} = 6.84$
2	$h(2,1) = \{v_1\}$; $h(2,2) = \{v_2, v_3, v_4, v_5, v_6\}$; $h(2,3) = \{v_7, v_8, v_9, v_{10}, v_{11}\}$	$\sigma_x^{h(2,2)} = 0.43$ $\sigma_x^{h(2,3)} = 1.29$	$\sigma_y^{h(2,2)} = 0.31$ $\sigma_y^{h(2,3)} = 3.45$
3	$h(3,1) = \{v_1\}$; $h(3,2) = \{v_2, v_3, v_4, v_5\}$; $h(3,3) = \{v_6\}$; $h(3,4) = \{v_7\}$; $h(3,5) = \{v_8, v_9, v_{10}, v_{11}\}$	$\sigma_x^{h(3,2)} = 0$ $\sigma_x^{h(3,5)} = 0$	$\sigma_y^{h(3,2)} = 0.22$ $\sigma_y^{h(3,5)} = 0.23$
4	$h(4,1) = \{v_1\}$; $h(4,2) = \{v_2\}$; $h(4,3) = \{v_3, v_4, v_5\}$; $h(4,4) = \{v_6\}$; $h(4,5) = \{v_7\}$; $h(4,6) = \{v_8\}$; $h(4,7) = \{v_9, v_{10}, v_{11}\}$	$\sigma_x^{h(4,3)} = 0$ $\sigma_x^{h(4,7)} = 0$	$\sigma_y^{h(4,3)} = 0.24$ $\sigma_y^{h(4,7)} = 0.20$
5	$h(5,1) = \{v_1\}$; $h(5,2) = \{v_2\}$; $h(5,3) = \{v_3\}$; $h(5,4) = \{v_4, v_5\}$; $h(5,5) = \{v_6\}$; $h(5,6) = \{v_7\}$; $h(5,7) = \{v_8\}$; $h(5,8) = \{v_9\}$; $h(5,9) = \{v_{10}, v_{11}\}$	$\sigma_x^{h(5,4)} = 0$ $\sigma_x^{h(5,9)} = 0$	$\sigma_y^{h(5,4)} = 0.20$ $\sigma_y^{h(5,9)} = 0.25$
6	$h(6,1) = \{v_1\}$; $h(6,2) = \{v_2\}$; $h(6,3) = \{v_3\}$; $h(6,4) = \{v_4\}$; $h(6,5) = \{v_5\}$; $h(6,6) = \{v_6\}$; $h(6,7) = \{v_7\}$; $h(6,8) = \{v_8\}$; $h(6,9) = \{v_9\}$; $h(6,10) = \{v_{10}\}$; $h(6,11) = \{v_{11}\}$		

Table 2. Holons composition in holarchy presented in Fig 6

The interest of this work (the holarchy) is to switch between abstraction level according to simulation objective (visualization ...) or computational resources. For example, if computational resources is available, the system can be modeled at the most precise level (microscopic). Nevertheless, if computational resources is insufficient, system can be modeled at level 5, level 4, level 3 etc. The main research question is therefore to ensure the consistency of the upper level modeling. Standard deviation helps us to ensure this consistency. For example in our example, at level 0, the value of standard deviation of interdistance is high: that's mean the gaps between vehicles is very dispersed: the gap between vehicles is not homogeneous. Moreover, the value of standard deviation of speed vehicles is high: that's mean the values of vehicles speeds are very dispersed. The speeds of vehicles are therefore not homogeneous. We can conclude saying that a holon $h(0,1)$ seems not to be a good approximation of its sub-holons. Nevertheless, at level 4 of holarchy the values of standard deviation tends to zero that means, vehicles seems to have sensibly the same speed, and gap between vehicles seems to be approximative. These group of vehicle are called convoy. We can conclude saying if computational resources is not available, this system can be well modeled at level 4, level 5 etc.

Convoy is a group of "similarity" vehicles because, in a convoy vehicle seems to have approximatively the same speed and approximatively the same inter-distance between them. Formally, convoy can be define as simple directed, planar, connected and acyclic weighted sub-graph on vertices and edges as in Eq. 6. In contrary with road traffic graph which is not necessarily connected convoy is always a connected graph.

$$G' \subseteq G \quad \text{such that} \quad G' = ((V', E'),\ \mathcal{W}_{E'}, \mathcal{W}_{V'}), \quad \sigma_{\mathcal{W}_{E'}} \leq \epsilon_1,\ \ \sigma_{y(V')} \leq \epsilon_2)) \tag{6}$$

$\epsilon_1 \rightarrow 0$ is the maximum standard deviation of inter-distance. $\epsilon_2 \rightarrow 0$ is the maximum standard deviation of speed. These values can be studied throw real observation of convoy.

An agent which plays the role `Head` of convoy is a vertex $v \in V$ such that output degree equals zero.

4 Experimental Results

In order, to verify the relevance of our top down decomposition algorithm, an evaluation of the algorithm execution cost is needed. We have used SARL [18] language and Janus [9] run-time environment for our algorithm implementation. SARL is a general-purpose agent-oriented programming language which focus on holonic modeling and simulation. Tests were performed on a desktop, Pentium III, 800 MHz, 512 MB of RAM. Fig 7 presents the performance of our algorithm execution with three traffic conditions. The corresponding linear regression line which approximate the average traffic distribution has the following equation: $y = 0.057747x + 0.809038$. We can therefore assert that the execution of our algorithm has a good performance because the slope of the linear regression tends to zero.

It should be noted that the internal states of the agents are generated for running the model. They should be replaced by internal states issued from field interviews.

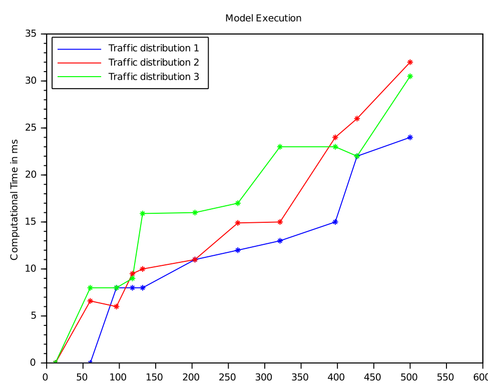

Fig. 7. Our algorithm performance

5 Conclusion and future works

Holonic multiagent systems are an effective tool to model traffic [10]. The first issue concerning holonic systems is the way how holarchy is structured (presentation of the whole containing/contened element of system) at time $t = 0$. This papers has presented a top down decomposition of road traffic system based on holonic multiagent systems. Then, several multilevel indicators are also proposed, based on standard deviation, in order to evaluate the consistency of the created holons.

Road traffic is a open system and need to manage the holarchy builded over time. The main research questions to this end are how to manage a new holon in system? How can a sub-holon can be leave his super-holon if it's not meets more the criteria of the group? How a holon can join a new group of holons? Future works include dynamic self-organization of the holons over time and proposition of others multilevel indicators taking into account spatio-temporal properties and driver behaviors.

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