System of Systems Approach for Modeling an ITS

Pushpendra Kumar, Rochdi Merzouki, and Belkacem Ould Bouamama

***Abstract*ð In the present work, an Intelligent Transportation System (ITS) is modeled based on the System of Systems (SoS) approach. A SoS is large-scale integrated system which can be organized into various levels according to their complexity. Thus, the traffic dynamic in an ITS can be classified into three abstraction levels of a SoS namely: submicroscopic, microscopic, and macroscopic level models. These three levels are combined to develop a multilevel model of the traffic dynamic in an ITS. This multilevel model is developed using the Bond graph modeling approach. Finally, the model is simulated for normal and disturbed scenarios in the traffic SoS.**

Keywords*ð *Intelligent Transportation System; System of Systems; Modeling; Bond Graph.

I. Introduction

For sustainable transport, it is very important to achieve the smooth flow of traffic on roads, because road transport is the dominant means of transport in EU-27 both for passengers and freight. Congested traffic leads to an increase in the cost of transport, pollution, accidents, and travel time. Here, we consider the traffic flow in an ITS. An ITS helps in having smooth traffic flow on roads, moreover, it can be a solution for space optimization problem in a confined space like port terminal environment.

Modeling of an ITS is important to understand the behavior of the traffic dynamic in it. Having a good traffic model allows better prediction of the traffic behavior on the road. In addition, the model can be used for supervision purpose to achieve better operational efficiency for an ITS. An ITS can be modeled as a SoS because of its large-scale and complexity of the constituent systems [1].

The proliferation of new Information and Communication Technologies (ICTs) has increased the complexity of the traditional systems, in addition, the integration of these complex systems. That led to the introduction of the concept of SoS. Maier [2] described the five properties to characterize a SoS: *operational independence, managerial independence, geographical distribution, emergent behavior, and evolutionary development*. Jamshidi [3] defined SoS as follows: *Systems of systems are large-scale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal.*

An ITS is composed of many Intelligent Autonomous Vehicles (IAVs) which operate to achieve some specific tasks towards a common mission, where, IAVs exchange information among them based on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. Such set of autonomous vehicles can describe an organization of a SoS because each IAV is operationally and managerially independent; they are dispersed geographically with a continuous exchange of information; furthermore, they can structurally make a self-reconfiguration of their organization.

The traffic dynamic in an ITS can be classified according to the level of details with which they represent the traffic system. Thus, the traffic models can be classified into four types: submicroscopic, microscopic, mesoscopic, and macroscopic [4]. In the present work, we don't consider the mesoscopic level model. Submicroscopic level models describe the dynamics of an individual vehicle including its various components [5]. Microscopic level describes the dynamics of the interaction between the vehicles, where the follower vehicle's motion is determined according to the motion of the leader vehicle [6]. Macroscopic level describes the whole traffic dynamics without distinguishing its constituent systems [7].

In this paper, the main contribution is to model the traffic dynamic in an ITS based on the SoS approach. Thus, from SoS point of view, all the levels of the traffic dynamic are combined to develop a multilevel model which can be used for supervision purpose in an ITS. Kumar [8] proposed a multilevel model of the traffic dynamic using the bond graph modeling approach.

II. Representation of a SoS

A SoS is composed of many operationally independent systems which are themselves complex and generally known as Component Systems (CSs) of that SoS. A SoS can be organized into various levels based on its CSs. In a multilevel SoS model, all the physical CSs are given at the lowest level, while their organizations at the higher levels represent the non-physical CSs.

For example, the port terminal system can be seen as a SoS as given in Fig. 1. It can be observed that the port terminal system is a large-scale system, and can be organized into multilevels of a SoS namely submicro, micro, and macro levels. It is composed of many heterogeneous complex systems which represent physical CSs of a SoS with multi-structures. Each CS is assigned with a mission, and the cooperation of multi-missions results in achieving the global mission of the considered SoS.

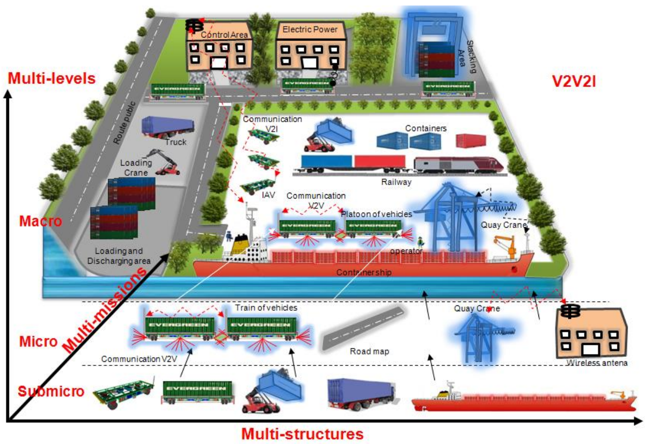

Fig. 1. Multilevel representation of the port terminal SoS.

The authors are with the Laboratoire dôAutomatique, Génie Informatique et Signal (LAGIS), UMR CNRS 8219, Polytech Lille, University of Lille 1, 59655 Villeneuve dôAscq, France (e-mail: jahan.pushp@gmail.com; rochdi.merzouki@polytech-lille.fr; belkacem.ouldbouamama@polytech-lille.fr).

Refer to Fig.1, the submicro level represents the physical CSs; in this case, the physical CSs include IAVs, loading cranes, trucks, container ships, etc. The micro level represents the organizations of submicro level CSs based on communication among them, which include V2V and V2I communication. Finally, the whole SoS can be realized at the macro level. Thus, a port terminal system shows the properties of SoS, because all the physical CSs at the lowest level are operationally and managerially independent to complete their tasks. They communicate with each other while geographically dispersed, and cooperate to achieve the global mission of the SoS.

III. Modeling of the Traffic Dynamic in an ITS

Modeling of a SoS is challenging because of its complexity and lack of well established principles for the engineering of a SoS [9]. Most of the existing models in literature are based on the organizational modeling approach, which don't provide the dynamic behaviroal models of the physical CSs of a SoS [10], [11]. The behavirol modeling is important for the whole supervision of a SoS. Thus, it is required to develop a SoS model which can combine organizational and behavioral modeling approaches.

The traffic dynamic in an ITS can be represented with three abstraction levels of a SoS namely: submicroscopic, microscopic, and macroscopic (Fig. 2). An ITS consists of IAVs, intelligent infrastructures, embedded hardware and software equipments, etc.; V2V and V2I communication takes place among these entities using various ICT tools.

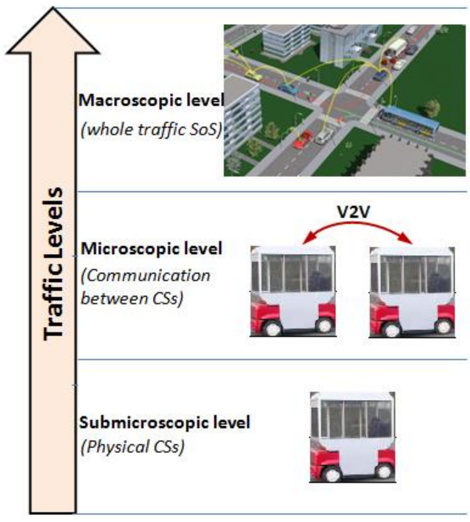

Fig. 2. Multilevel representation of the traffic dynamic in an ITS as a SoS.

Refer to Fig. 2, the submicroscopic level represents the physical CSs (IAVs); the microscopic level represents the organization of the physical CSs based on V2V communication; and the macroscopic level represents the whole traffic SoS. In the present work, three levels are modeled using Bond graph modeling approach. Bond graph is a unified modeling approach which is based on the power exchange between systems, and applicable on systems of various domain viz. mechanical, electrical, thermal, etc. [12]. Finally, three levels of the traffic dynamic are combined to develop a multilevel model of an ITS as a SoS. A multilevel model of the traffic dynamic has been developed in [8], which is described in the following subsections.

A. *Submicroscopic modeling*

At the submicroscopic level, the dynamic models of IAVs are developed. Here, an IAV called RobuCar is considered which is shown in Fig. 3 (a). The schematic top view of the IAV is shown in Fig. 3 (b).

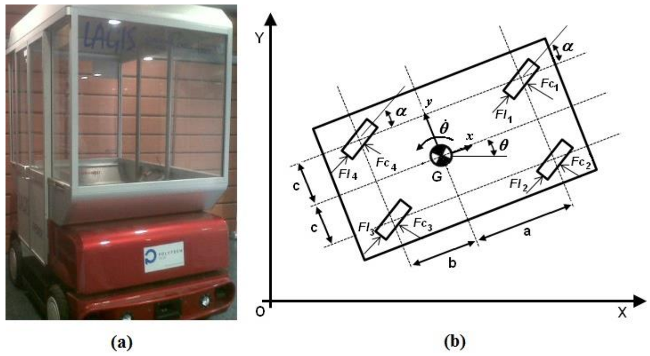

Fig. 3. (a) IAV- RobuCar (b) Schematic top view of the IAV.

The considered IAV has four traction wheels actuated by four independent direct current (dc) motors and all the wheels are steerable. The IAV is equipped with an inertial sensor to measure its longitudinal, lateral, and yaw speeds. Also, sensors are mounted to measure the angular speed of each wheel and the current drawn by each motor. The following dynamics are considered for modeling: (i) traction actuators, slip and steering dynamics of the wheels and (ii) longitudinal, lateral and yaw dynamics of the vehicle's centre of mass (CM).

The complete bond graph model of an IAV considering all the dynamics is shown in Fig. 4. Fig. 4(a) shows the dynamics of vehicle's CM, where *m* and *J* represent mass and polar moment of inertia of the vehicle, respectively. The dimensions of the vehicle are denoted by *a*, *b* and *c* in the modulous of transformer elements. The full-headed arrows corresponding to the speeds $(\dot{x}, \dot{y}, \dot{X}, \dot{Y}$ and $\dot{\theta})$ of the vehicle's CM, represent the sensors to measure the value of the corresponding parameter.

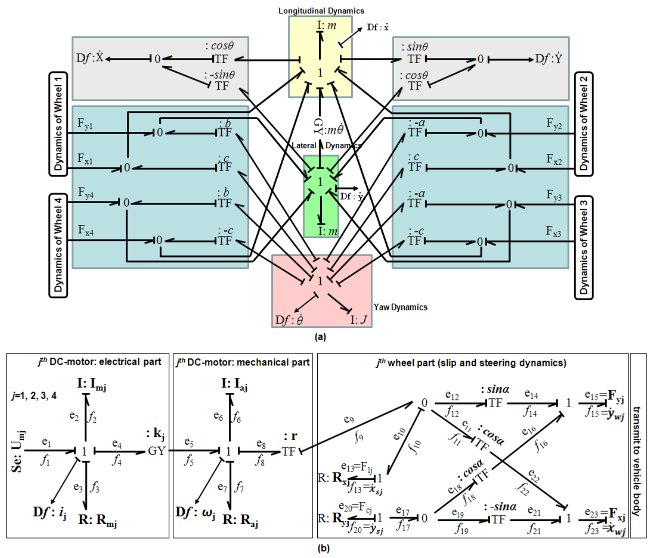

Fig. 4. Bond graph model of an IAV: (a) dynamics of the vehicle' CM (b) dynamics of the wheel.

The IAV is composed of four quarters i.e., wheel-1, 2, 3, and 4. Let us consider the dynamic of the wheel-j (j=1,2,3 or 4) as shown in Fig. 4(b). The wheel dynamic is composed of electric part of motor, mechanical part of motor, and slip and steering dynamics. In electrical part of the motor, U_{mj}, I_{mj}, R_{mj} and k_j represent voltage, inductance, resistance and torque constant of the motor, respectively. In mechanical part of the motor, I_{aj} and R_{aj} represent polar moment of inertia and friction of the wheel-axle, respectively. Angle δ is the steering angle, and r is the radius of the wheel. R_{xj} and R_{yj} represent the slip contribution in x and y directions, respectively, e_n and f_n represent the effort and flow, respectively in n^{th} bond (n=1,2,3...). The full-headed arrows corresponding to current i_j in motor and angular speed of the wheel axle ω_j represent the sensors to measure the value of the corresponding parameter.

The voltage source (Se) provides voltage U_{mj} to the motor. The electric power of the motor is converted into mechanical power with the help of gyrator element (GY). The longitudinal and lateral speeds of the wheel x_{wj} and y_{wj}, respectively in conjunction with wheel's spinning speed generate the longitudinal and lateral slip speeds x_{sj} and y_{sj}, respectively. The longitudinal force F_{lj} and cornering force F_{cj} are functions of the longitudinal and lateral slip speeds, respectively. F_{xj} and F_{yj} are the forces generated by the wheel in x and y directions, respectively, and are transmitted to the vehicle' CM in x and y directions, respectively. The speed of vehicle' CM in inertial frame X-Y is obtained by the transformation of x-y frame by angle ψ.

B. Microscopic modeling

At the microscopic level, the interection between IAVs is modeled in such a way that the follower IAV always tries to maintain a safe seperation (interdistance) with the leader IAV. This behavior is modeled assuming that the IAVs are connected by the spring-dashpot system. Actually, this physical connection is virtual and represents the stick-slip motion of between the IAVs [13].

In Fig. 5, a system of the leader (n) and the follower ($n+1$) IAVs is shown, where submicroscopic bond graph models of two IAVs are connected with the bond graph model of the spring-dashpot system, where bonds 2 and 1 connect the longitudinal dynamic junctions of the bond graph models of the leader and the follower IAVs, respectively. The full-headed arrow (bond 2) represents the flow activated bond, which transfers only flow f_2 to the system and the effort e_2 is zero. This describes that the two IAVs are not connected physically, and this connection is used to calculate the necessary effort e_1 to be applied on the follower IAV to maintain a safe interdistance.

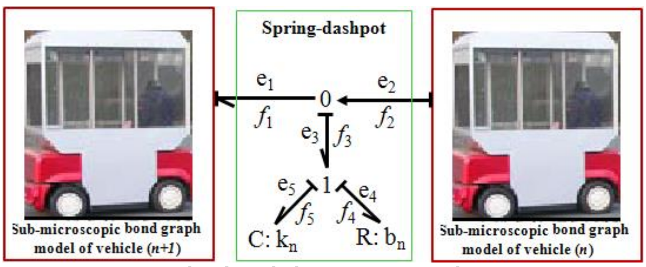

Fig. 5. Microscopic bond graph showing interaction between two IAVs.

C. Macroscopic modeling

At the macroscopic level, the average values of macroscopic traffic variables (flow, density and mean speed) can be deduced from the bond graph models of the microscopic and submicroscopic levels.

If s_n is the distance headway for n^{th} IAV which is given as (X_n-X_{n+1}), and the state value of the position X_n for each IAV is measured by the inertial sensor mounted on the vehicle, then average distance headway can be given by:

$$\overline{s} = \frac{1}{i}\sum_{n=1}^{i} s_n \tag{1}$$

where, i represent number of IAVs at any instant of time in the considered road section. The average density ρ of the traffic flow can be given in terms of average distance headway as following:

$$\rho = \frac{1}{\overline{s}} \tag{2}$$

If $\dot{X}_n$ is the speed of n^{th} IAV, which is measured by the flow sensor mounted on each vehicle, then space mean speed $\overline{v}$ can be given as follows.

$$\overline{v} = \frac{1}{i}\sum_{n=1}^{i} \dot{X}_n \tag{3}$$

Finally, flow of traffic q can be calculated from the fundamental relation of the traffic flow:

$$q = \rho.\overline{v} \tag{4}$$

D. Multilevel modeling

A multilevel model of the traffic dynamic in an ITS is developed by combining the three levels (submicroscopic, microscopic, and macroscopic) based on the SoS approach (Fig. 6).

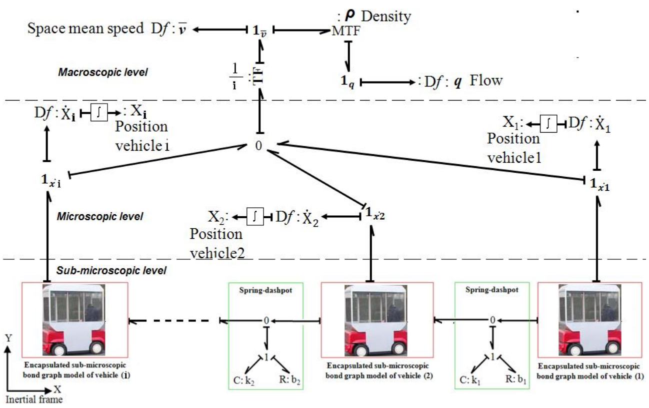

Fig. 6. Multilevel bond graph model of the traffic dynamic in an ITS as SoS.

In Fig. 6, the bond graph models of i number of IAVs are connected by the bond graph models of virtual spring-dashpot systems. The junctions $1_{\dot{X}_1}, 1_{\dot{X}_2} ... 1_{\dot{X}_i}$ represent the speeds of IAVs 1, 2...i, respectively with respect to inertial frame, and the full-headed arrows represent the sensors to measure the speeds $\dot{X}_1, \dot{X}_2 ... \dot{X}_i$ of IAVs. The speeds of IAVs are integrated to get the positions $X_1, X_2 ... X_i$ of each IAV. The space mean speed $\overline{v}$ and flow q of the traffic are shown by the full-headed arrows sensors, while density ρ is calculated according to (1) and (2). In this way, the whole SoS is modeled considering traffic dynamic in an ITS using a single modeling approach Bond graph.

For more details of this multilevel model, one can refer to [8]. In addition, [14] used this multilevel model to apply the bond graph based methods of Fault Detection and Isolation (FDI) and reconfiguration of IAVs.

IV. Simulation Results

The model is simulated using a dedicated software for the bond graph modeling called Symbols. SYMBOLS stands for SYstem Modeling by BOndgraph Language and Simulation. Two scenarios are considered for simulation (i) normal operation in a platoon of four IAVs and (ii) situation of one IAV leaves the platoon.

A. First scenario

For the first scenario, a platoon of four IAVs is considered moving on a road in a straight line. The simulation results are shown in Fig. 7. In Fig. 7(a) and (b), the submicroscopic variables; currents in the four motors of vehicle 1 and the angular speeds of the four wheels of vehicle 2 are plotted with respect to time, respectively. In Fig. 7(c) and (d), the microscopic variables (position and speed) are plotted with respect to time; it can be observed that the leader (vehicle 1) is moving with a speed of 7.7 m/s and vehicle 2 follows it. It can be noticed that vehicle 2 changes its speed with respect to time to maintain the separation with vehicle 1, which represents the stick-slip motion between the leader and the follower vehicles for maintaining a safe interdistance. Similarly, vehicle 3 follows vehicle 2 and vehicle 4 follows vehicle 3.

In Fig. 7(e), the average distance headway between the vehicles is plotted with respect to time; it can be seen that there is a minimum average headway of 4.0 m at time 11.0 s, when all the four vehicles are very close. In Fig. 7(f)ï (h), the macroscopic variables (mean speed, density, and flow) are plotted with respect to time; the mean speed of the traffic changes with respect to time as the speed of each vehicle in the traffic is changing to maintain a safe interdistance between the vehicles. The density of the traffic is also changing and its maximum (246.9 veh/km) when the average headway is minimum at time 11.0 s, which represents the dense traffic. At time 10.3 s, flow of the traffic achieves its maximum value (5812.1 veh/h); at this instant of time, the values of density (228.4 veh/km) and mean speed (25.4 km/h) can be called critical density and critical speed, respectively.

B. Second scenario

For the second scenario, a platoon of four IAVs is considered moving on a road in a straight line, but after some time, vehicle 2 takes a turn at an intersection on the road and leaves the platoon. The simulation results are shown in Fig. 13. In Fig. 8(a) and (b), the submicroscopic variables; currents in the four motors of vehicle 1 and the angular speeds of the four wheels of vehicle 2 are plotted with respect to time, respectively. After 20 s, the angular speeds of the wheels of vehicle 2 start to decrease as it leaves the platoon. In Fig. 8(c) and (d), the microscopic variables (position and speed) are plotted with respect to time; it can be observed that the leader (vehicle 1) is moving with a speed of 7.7 m/s and vehicle 2, vehicle 3, and vehicle 4 follow their leading vehicle as described in the previous simulation. However, at time 20 s, vehicle 2 takes a turn at an intersection and its speed in the *x*-direction starts to decrease and, finally, becomes zero. Now, it is no longer in the platoon.

In Fig. 8(e), the average distance headway between the vehicles suddenly increases at time 20 s. In Fig. 8(f)ï (h), the macroscopic variables (mean speed, density, and flow) are plotted with respect to time. The behavior of the mean speed of the traffic is not much affected in this case compared with previous simulation. However, the density and the flow suddenly decrease at time 20 s because one vehicle is removed from the platoon.

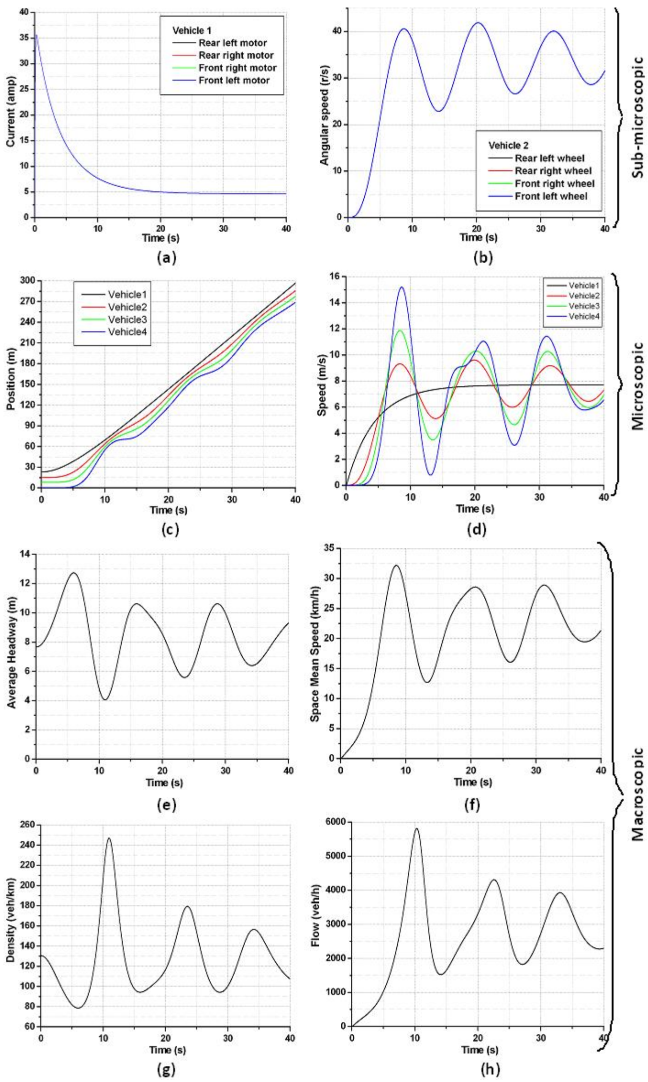

Fig. 7. First scenario (normal traffic operation). (a) Current in each motor of vehicle 1. (b) Angular speed of each wheel of vehicle 2. (c) Position of each vehicle. (d) Speed of each vehicle. (e) Average distance headway between vehicles. (f) Space mean speed of the traffic. (g) Density of the traffic. (h) Flow of the traffic with respect to time.

V. Conclusion

In this work, a multilevel model of the traffic dynamic in an ITS is proposed based on the SoS approach. This is achieved by modeling of the traffic dynamic at three abstraction levels of a SoS namely; submicroscopic, microscopic, and macroscopic. Finally, three levels are combined to develop a multilevel model using an unified modeling approach called Bond graph. The model includes not only the organizational modeling but also the behavioral modeling of the physical CSs (IAVs) of the considered SoS i.e., ITS. This model can be used for supervision of an ITS by applying bond graph based methods for FDI and reconfiguration.

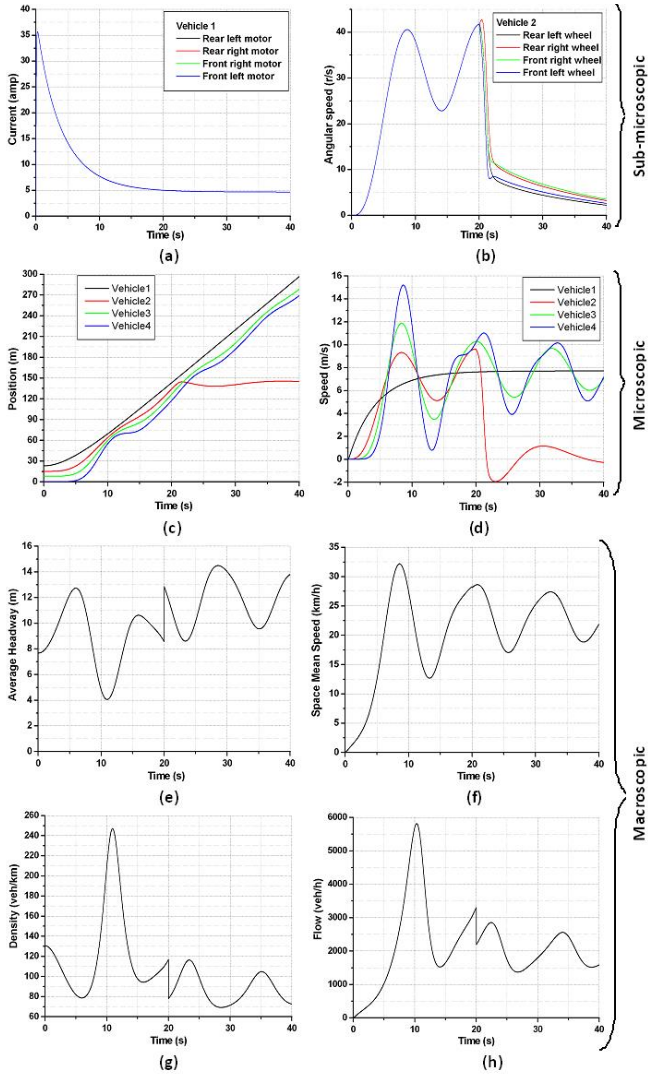

Fig. 8. Second scenario (one vehicle leaves the platoon). (a) Current in each motor of vehicle 1. (b) Angular speed of each wheel of vehicle 2. (c) Position of each vehicle. (d) Speed of each vehicle. (e) Average distance headway between vehicles. (f) Space mean speed of the traffic. (g) Density of the traffic. (h) Flow of the traffic with respect to time.

ACKNOWLEDGMENT

The authors would like to thank the European projects Weastflows (196G) and InTraDE (091C) from INTERREG IVB North-West Europe for supporting the present work.

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