Annex: Simulation proofs

1. Conventions

We start by defining the conventions used for the presentation of some results of the simulations conducted under the VEINS framework.

- In SUMO simulator, the Host Vehicle (HostVeh) is colored in yellow and the other vehicles, *i.e.*, Target Vehicles, (TargVeh) are colored in red.
- In OMNET++ simulator, vehicles are considered as nodes represented by red rectangles. A node surrounded by a red (light) circle shows that the vehicle concerned has identified a risk of collision in the predictable or unpredictable collision zone. While a node surrounded by a green circle shows that the concerned vehicle did not detect a risk of collision during its path.

Figure A1 shows the parallel execution of the two simulators SUMO and OMNET++ after their integration in the VEINS Framework. The left part of the screenshot concerns the SUMO simulator and the right part of the screenshot concerns the OMNET++ simulator.

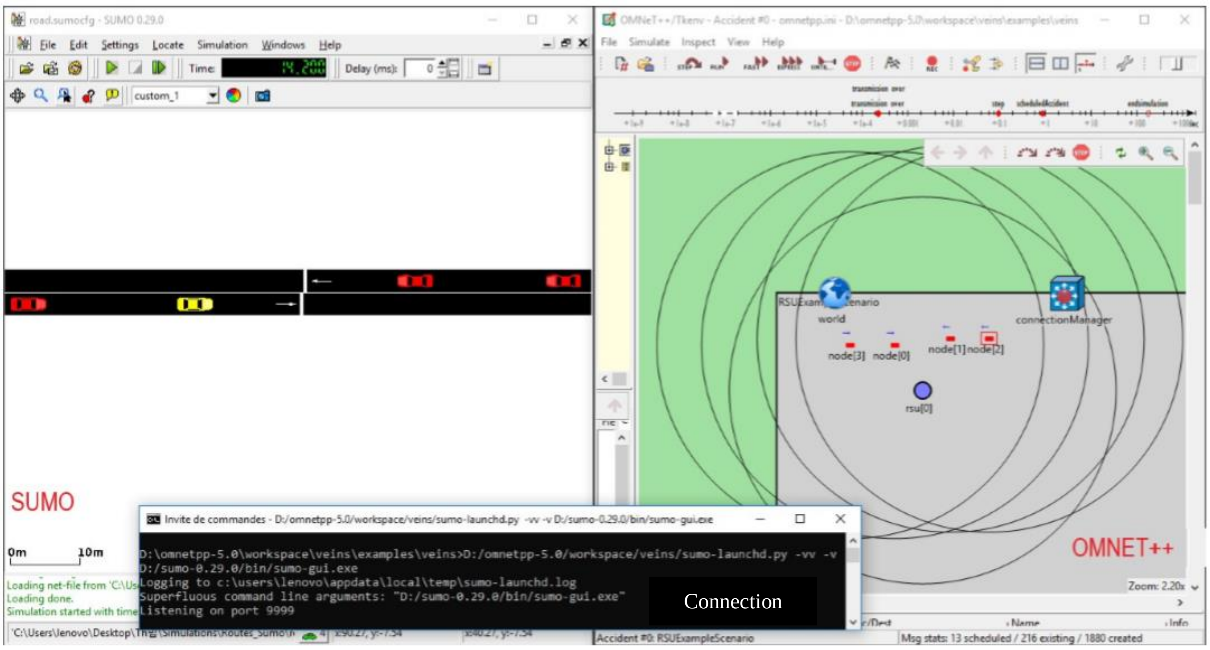
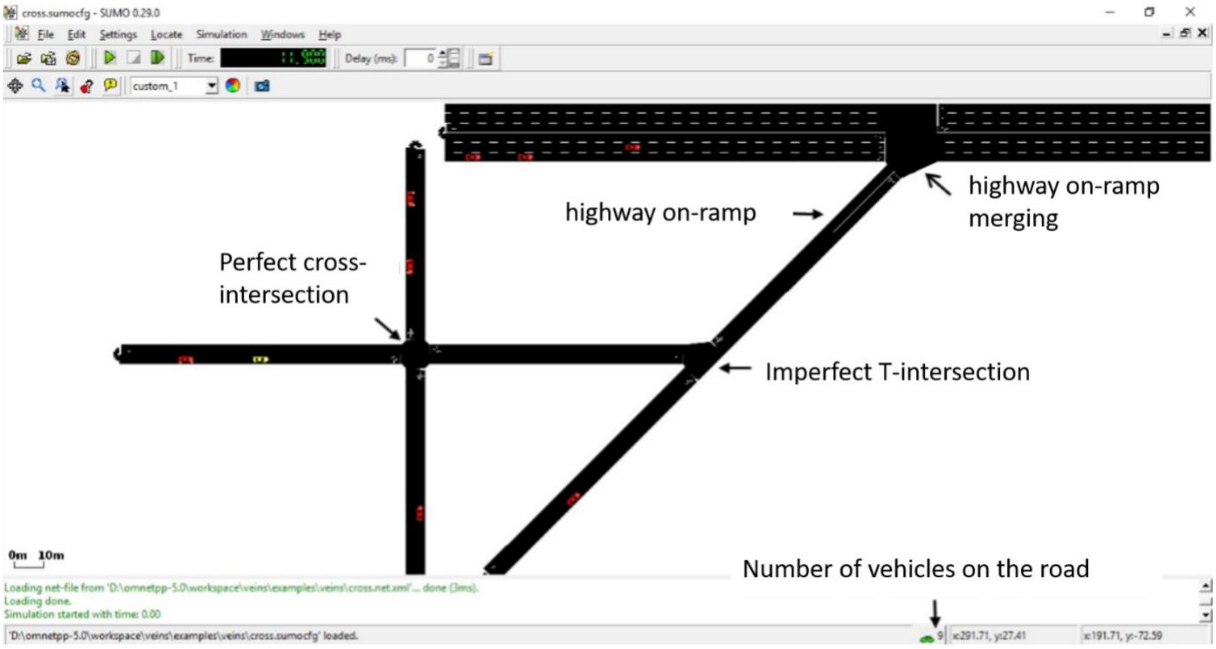


Figure A1. *Screenshot of the graphical interfaces of the SUMO and OMNET++ simulators following their parallel execution*

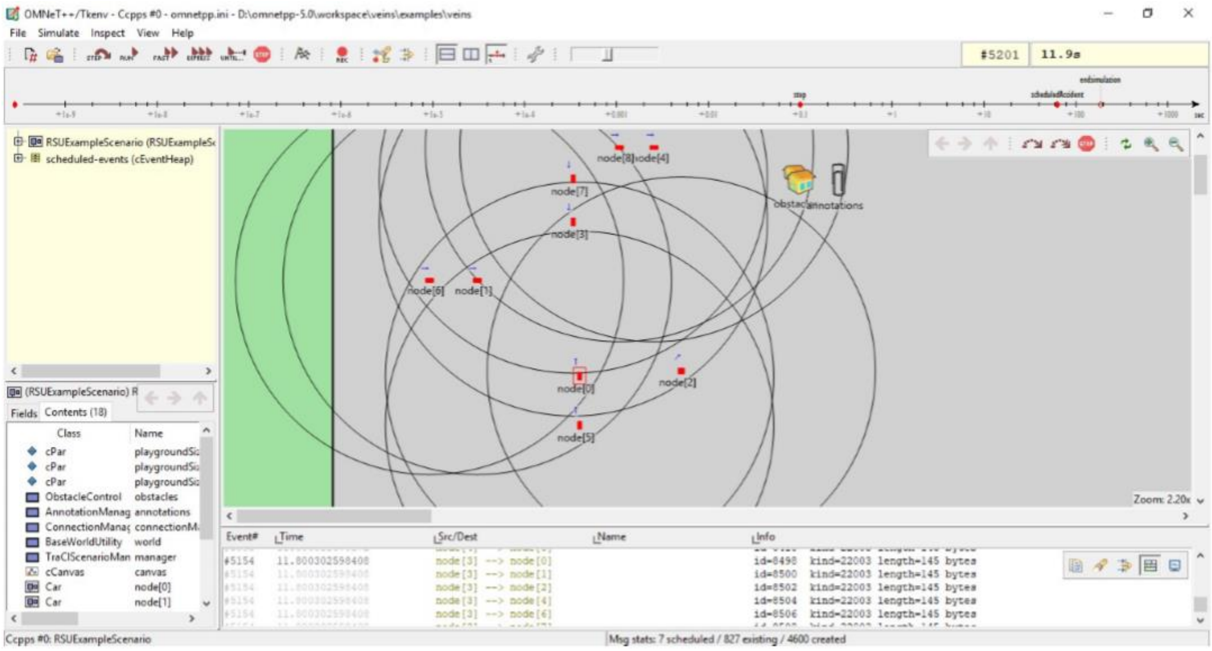
2. First series of simulations

In order to test the efficiency of our CCPPS subsystem, we simulated the operation of its three components (CICA[1], CLTA[2] and CHRM[3]) together using approximately ten simulations. Figure A2 shows the scenario where a HostVeh (yellow vehicle in figure A2 (a)) passes first through a perfect cross intersection, then through an imperfect T-intersection, and finally through a highway on-ramp merging. Throughout its journey, the HostVeh meets TargVeh that circulate randomly (red vehicles in the figure A2 (a)).

[1] Cooperative Intersection Collision Avoidance
[2] Cooperative Left Turn Assistance
[3] Cooperative Highway on-Ramp Merging



(a)



(b)

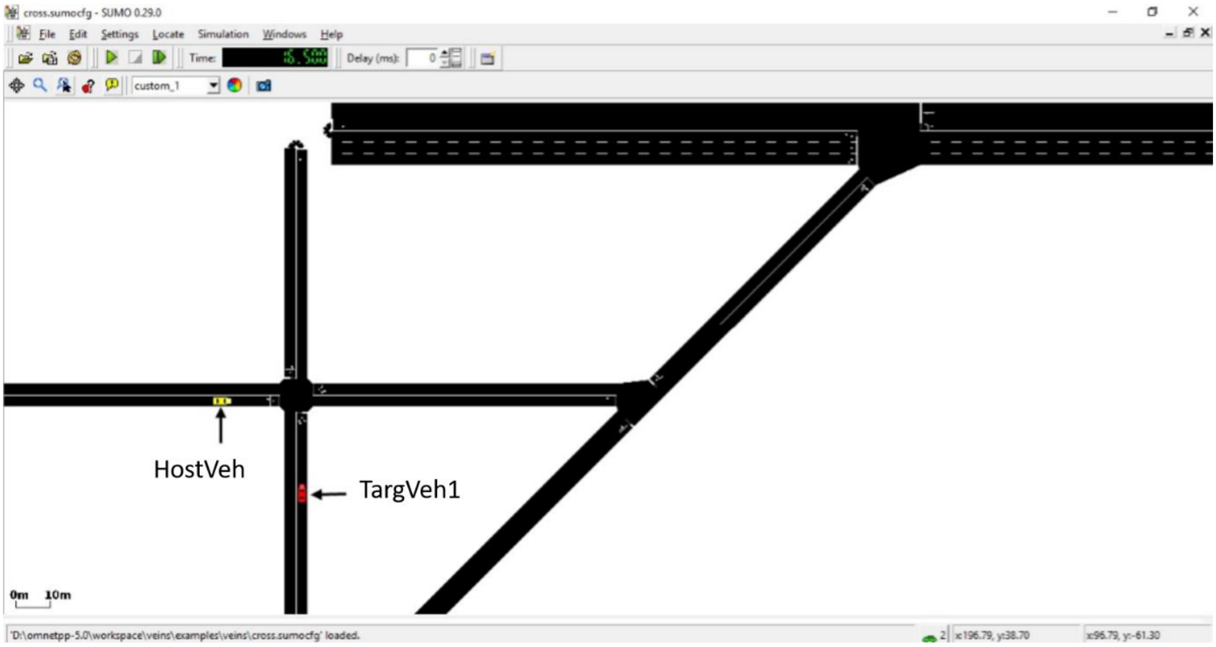
Figure A2. *Screenshots of a scenario where vehicles randomly circulate in three risk zones under the simulators (a) SUMO and (b) OMNET++.*

We have tested this scenario several times for three cases: (i) the existence of a collision risk in each of the three risk zones, (ii) the absence of collision risks in all three zones, and (iii) the existence of a collision risk in one or two of the three zones. However, we restrict here to present only one case where the HostVeh has detected a collision hazard in the perfect cross-intersection and in the merging of the highway on-ramp and has not detected a hazard in the imperfect T-intersection. The results of these simulations are shown in Figures A3, A4, and A5, which show the passage of the HostVeh successively through the perfect cross-intersection, the imperfect T-intersection and the highway on-ramp, respectively. Table A1 shows the entry time and exit time of the HostVeh in the high-risk collision zones of these three hazardous zones. This table also shows the entry and exit times of the three TargVeh in the high-risk collision zones encountered on their journeys.

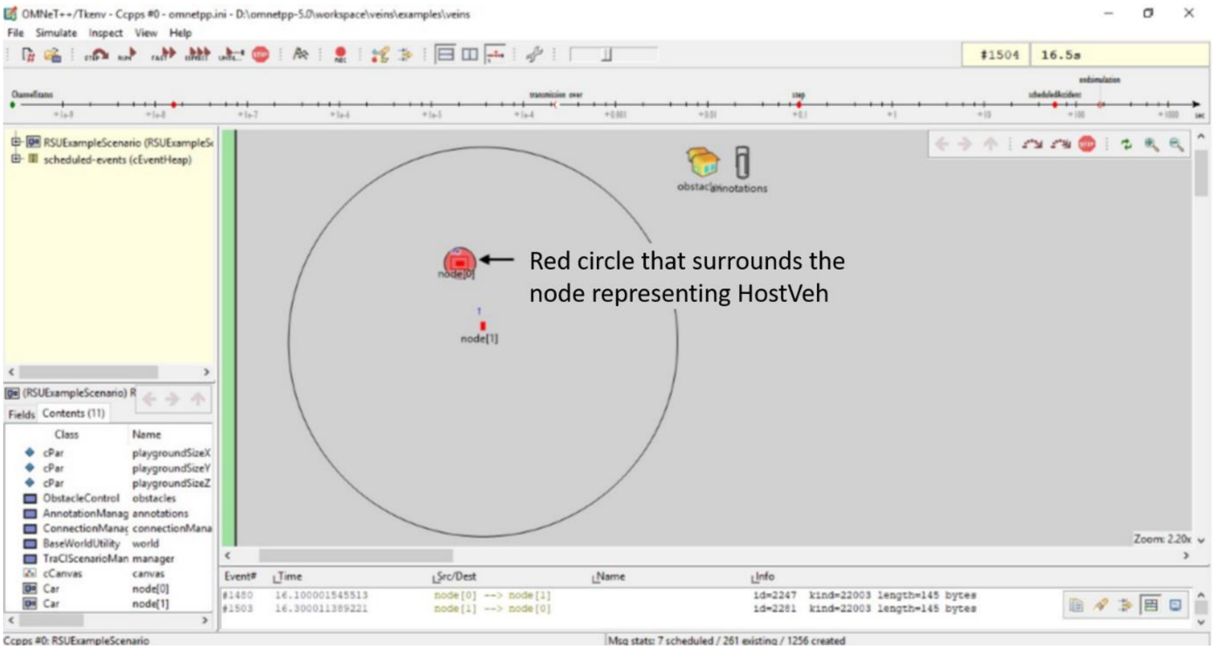
Table A1. *Entry and exit times of HostVeh and TargVeh in high-risk collision areas*

Vehicle type	**Type of the risk area**	**Time to enter to the high-risk area**	**Time to exit the high-risk area**
HostVeh	perfect cross intersection	79 s	84 s
TargVeh1	perfect cross intersection	80 s	91 s
HostVeh	Imperfect T-intersection	108 s	114 s
TargVeh2	Imperfect T-intersection	123 s	129 s
HostVeh	Highway on-ramp merging	136 s	152 s
TargVeh3	Highway on-ramp merging	137 s	143 s

Figure A3 shows that the HostVeh Intersection Manager has identified a risk of collision with TargVeh1 in the perfect cross intersection. This is illustrated by the red circle around the node representing the HostVeh in the OMNET++ simulator (*cf.* figure A3 (b)). Table A1 shows that the times of the inputs of the HostVeh and TargVeh at the perfect cross-intersection are very close. They are equal to 79 s for HostVeh and 80 s for TargVeh1. In this case, HostVeh has priority knowing that it is on a primary road. Hence, the HostVeh crosses the intersection first, while TargVeh1 decelerates to wait for the passage of HostVeh. The crossing times of the HostVeh and the TargVeh1 are equal to 5s (84s-79s) and 11s (91s-80s), respectively.



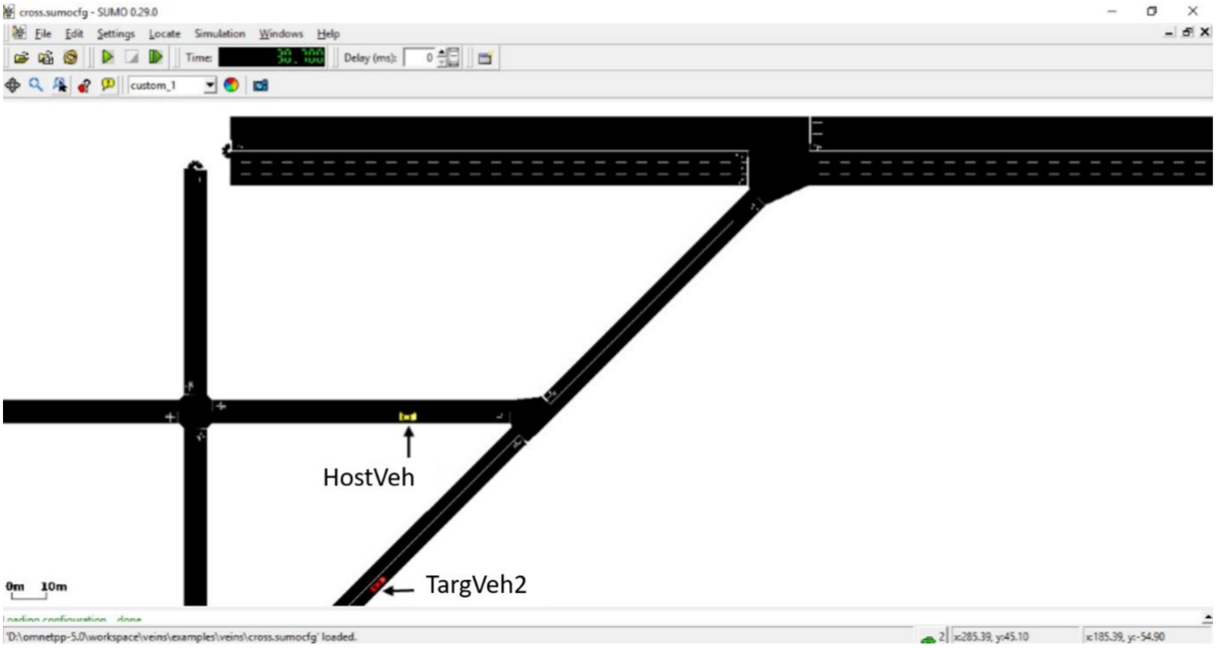
(a)



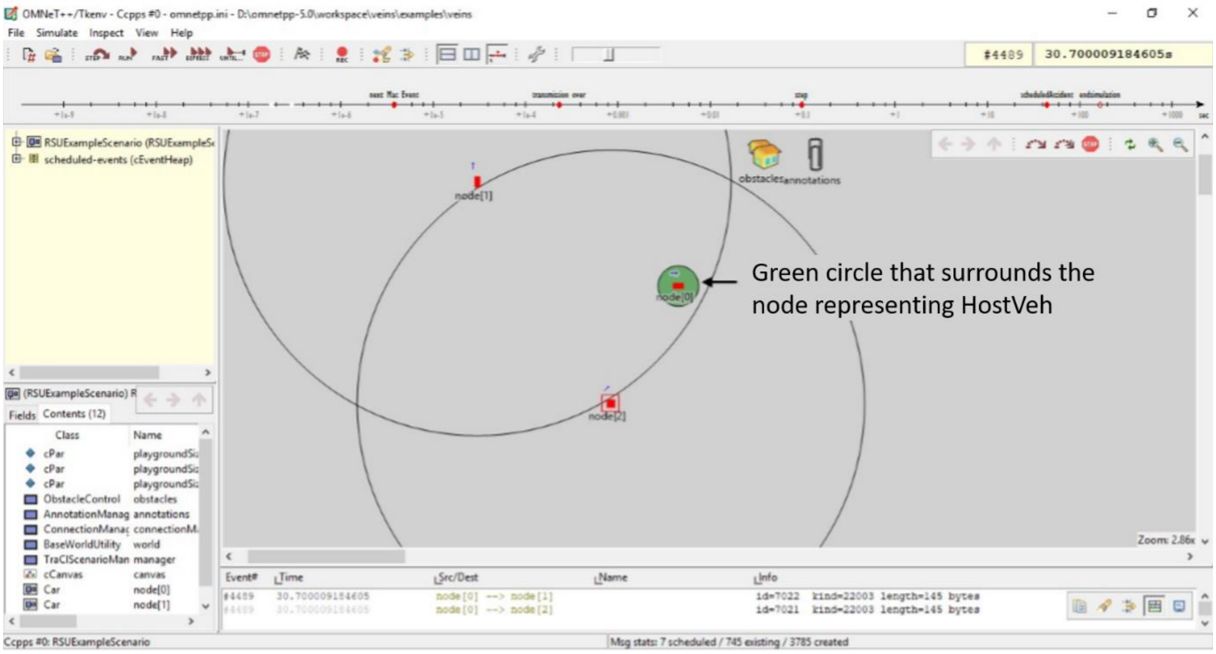
(b)

Figure A3. *Screenshots showing the detection of a collision risk between two vehicles in a perfect cross intersection under the simulators (a) SUMO and (b) OMNET++.*

Figure A4 shows that the HostVeh Intersection Manager did not detect a collision risk with TargVeh2 in the imperfect T-intersection. This is explained by the green circle surrounding the node representing the HostVeh (*cf.* figure A4 (b)). Table A1 shows that the time inputs of the HostVeh and TargVeh2 at this T-intersection are far away. They are equal to 108 s and 123 s for HostVeh and TargVeh2, respectively, hence the absence of a collision risk. The HostVeh therefore turned left safely with duration of 6 s (114 s - 108 s).



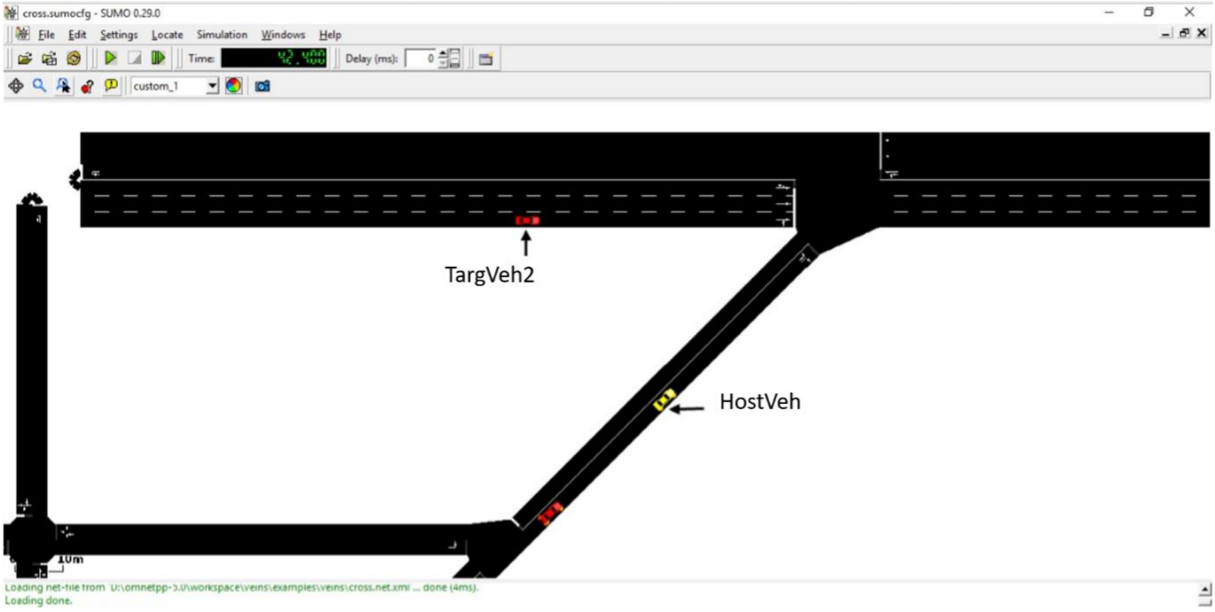
(a)



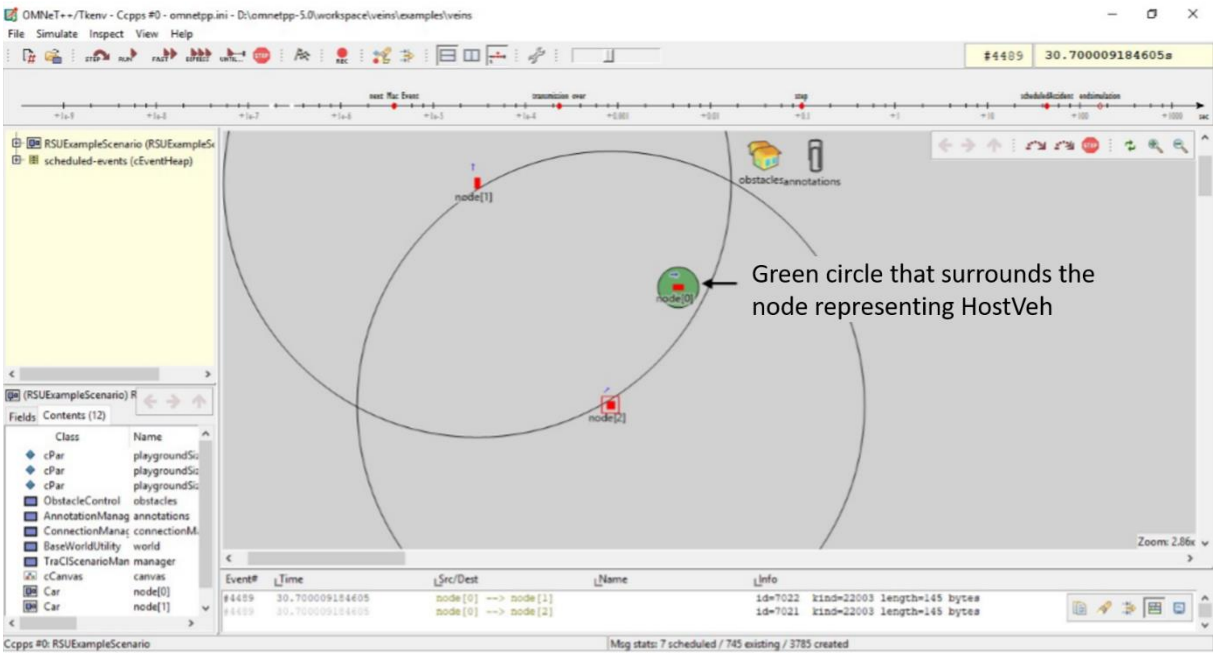
(b)

Figure A4. *Screenshots of a case where there is no risk of collision between two vehicles in an imperfect T-intersection under the simulators (a) SUMO and (b) OMNET++.*

Figure A5 shows that the HostVeh Intersection Manager has detected a collision risk with TargVeh3, which is running on the first corridor of the highway, and is approaching at the highway on-ramp merging (*cf.* the red circle around the node representing HostVeh in figure A5 (b)). Table A1 shows that the time of entries of HostVeh and TargVeh3 at the on-ramp highway merging are very close. They are equal to 136 s and 137 s for HostVeh and TargVeh3, respectively. The TargVeh3 has the priority since it is on a highway; it continues its trajectory without stopping or even decelerating. The HostVeh has the lowest priority here since it arrives from a highway on-ramp: it decelerates and waits for the passage of the TargVeh3 to integrate into the highway. The time taken by the HostVeh and the TargVeh3 are equal to 16 s (152 s - 136 s) and 6 s (143 s - 137 s), respectively.



(a)



(b)

Figure A5. *Screenshots of a case where there is no risk of collision between two vehicles in a highway on-ramp merging under the simulators (a) SUMO and (b) OMNET++*

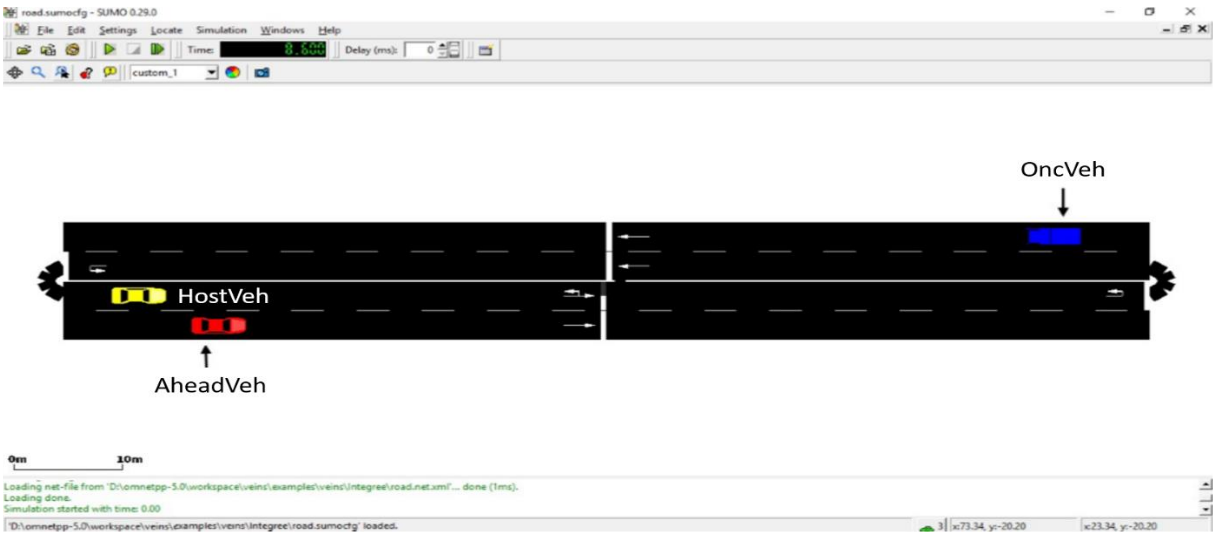
3. Second series of simulations

In this section, we present the effectiveness evaluation of the *Cooperative Overtaking Assistance Subsystem* (COAPS). In fact, we have simulated the functionality of COAPS using some forty simulations.

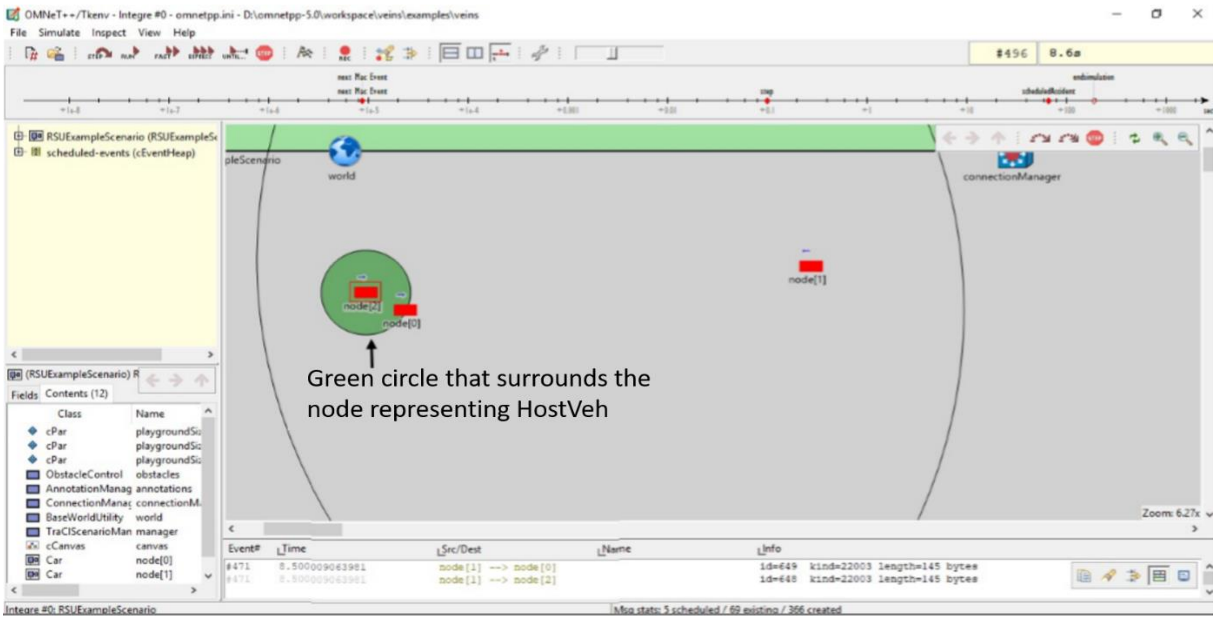
- **Case of authorized overtaking**

We have simulated COAPS functionality for the case of authorized overtaking with about twenty simulations. We tested the authorized overtaking of one vehicle, two vehicles and three vehicles. However, we restrict here to present two permitted overtaking scenarios: overtaking of only one vehicle and overtaking of three vehicles.

Figure A6 presents a scenario where a HostVeh wants to overtake a slower vehicle ahead (AheadVeh) while there is an oncoming vehicle (OncVeh) from the opposite direction. After analyzing the overtaking situation, the HostVeh Overtaking Manager authorizes the overtaking maneuver since the OncVeh is still far away (*cf.* figure A6 (a)). This is illustrated by the green circle surrounding the node representing the HostVeh in the figure A6 (b). Therefore, the HostVeh Movement Controller controls the overtaking maneuver by ordering the steering unit.



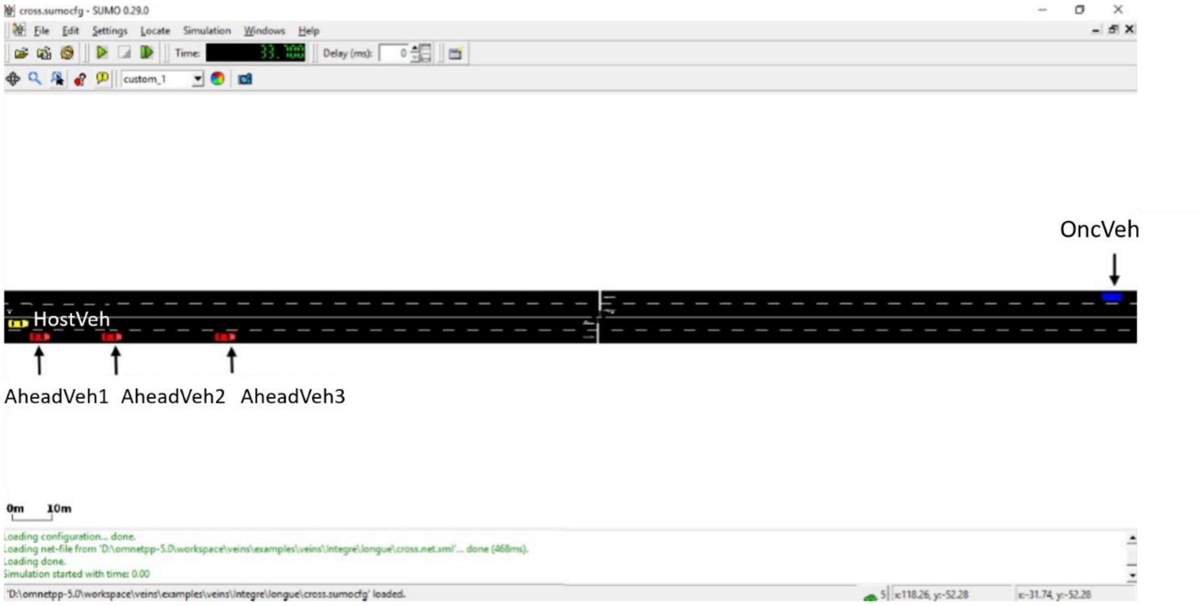
(a)



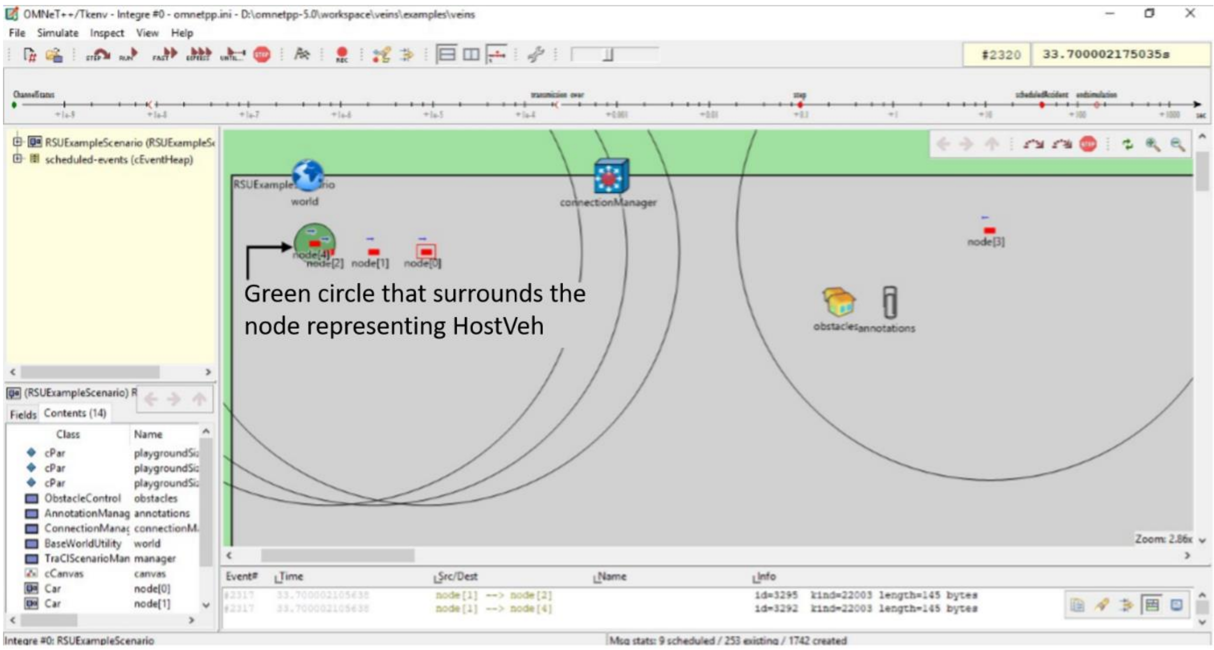
(b)

Figure A6. *Screenshots of an allowed vehicle overtaking scenario under the simulators (a) SUMO and (b) OMNET++.*

Figure A7 shows a scenario where the HostVeh wants to overtake three slower vehicles in front of it (AheadVeh1, AheadVeh2 and AheadVeh3) while a vehicle is approaching from the opposite lane (OncVeh). After analyzing the overtaking situation, the HostVeh Overtaking Manager authorizes the overtaking maneuver of the three vehicles since the OncVeh is far away (*cf.* figure A7 (a)). This is explained by the green circle around the node representing the HostVeh in figure A7 (b). Therefore, the HostVeh Motion Controller controls the overtaking maneuver by ordering the steering unit to switch the lane.



(a)



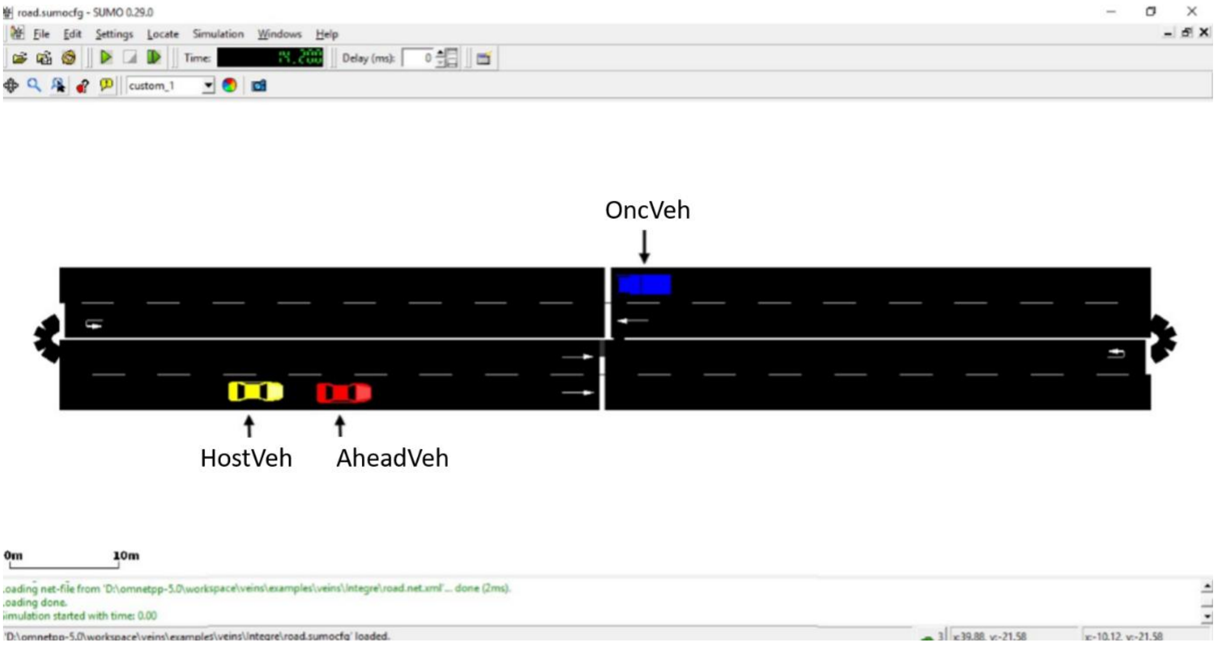
(a)

Figure A7. *Screenshots of a three-vehicle allowed overtaking scenario under simulators (a) SUMO and (b) OMNET++.*

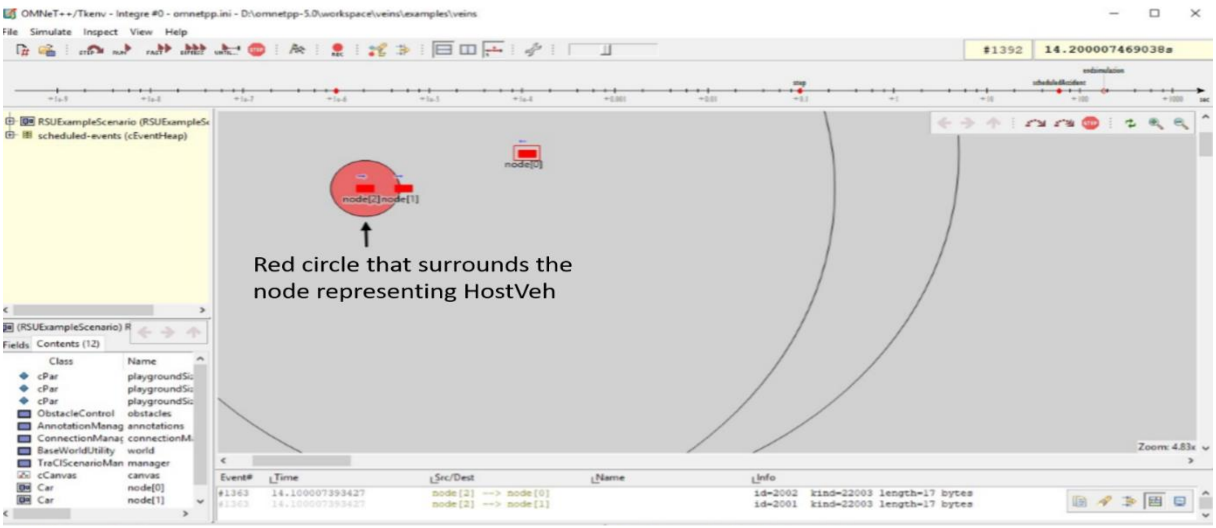
- **Case of unauthorized overtaking**

We have simulated the functionality of COAPS for the case of unauthorized overtaking, using about twenty simulations. We tested the unauthorized overtaking of one vehicle, two vehicles and three vehicles. However, we limit ourselves here to present only the scenario of unauthorized overtaking of a single vehicle.

Figure A8 shows a scenario where a HostVeh wants to overtake the AheadVeh while an OncVeh arrives from the opposite lane. After the analysis of the overtaking situation, the HostVeh Overtaking Manager decides to not authorize the HostVeh overtaking maneuver since the OncVeh is close, as shown by figure A8 (a). This is illustrated by the red circle surrounding the node representing the HostVeh in figure A8 (b).



(a)



(b)

Figure A9. *Screenshots of an unauthorized vehicle overtaking scenario under the simulators (a) SUMO and (b) OMNET++.*

For this scenario of unauthorized overtaking, the speed of the HostVeh is higher than the speed of the AheadVeh. In this case, the CACC component of the HostVeh is triggered in order to decrease its speed and maintain the safety distance with AheadVeh. This is illustrated by the blue circle surrounding the node representing the HostVeh in the figure 9.

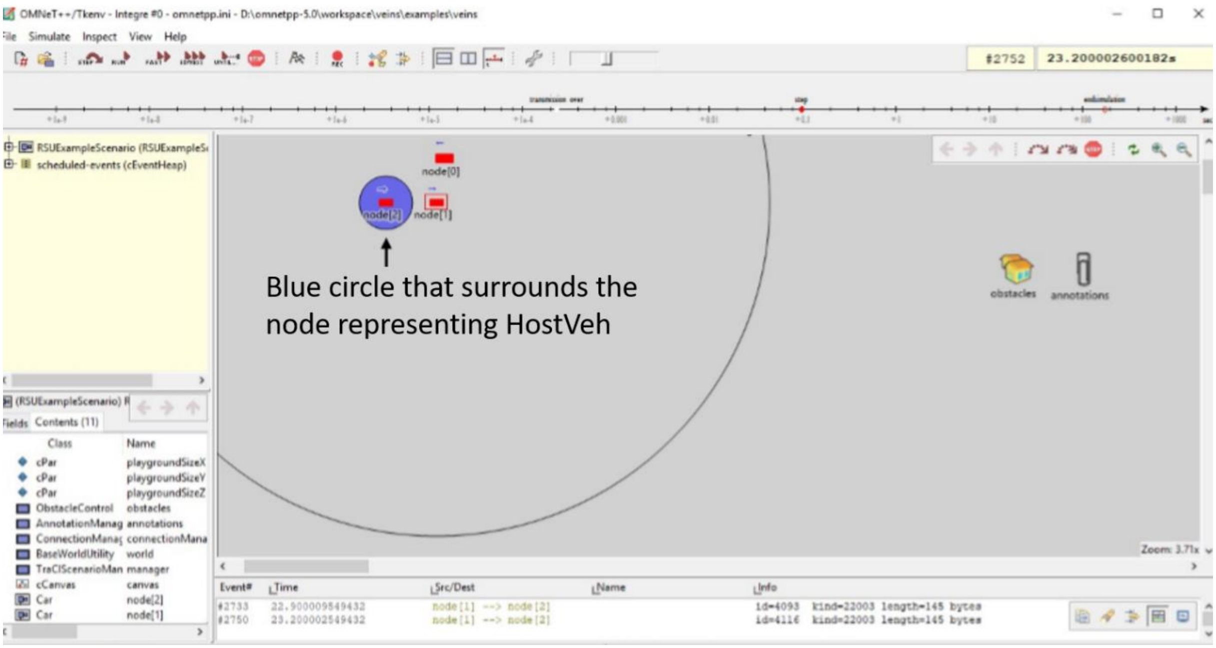


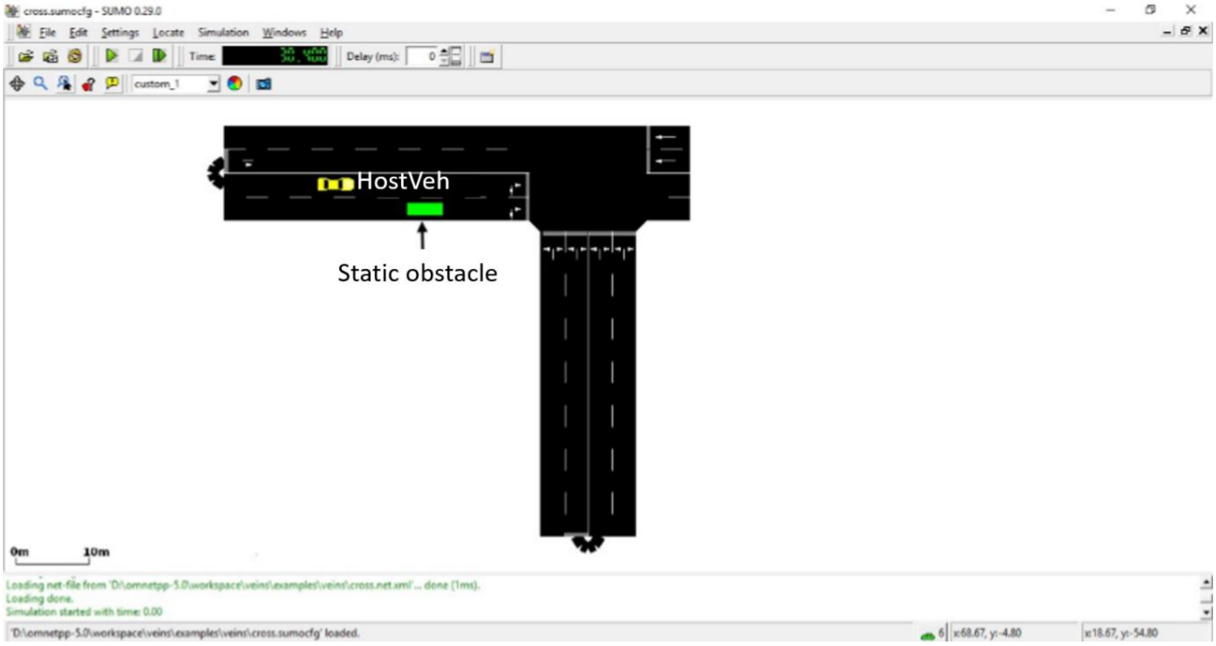
Figure A9. *Screenshot of a scenario where the CACC component is triggered when the overtaking maneuver is not allowed in the OMNET++ simulator.*

4. Third series of simulations

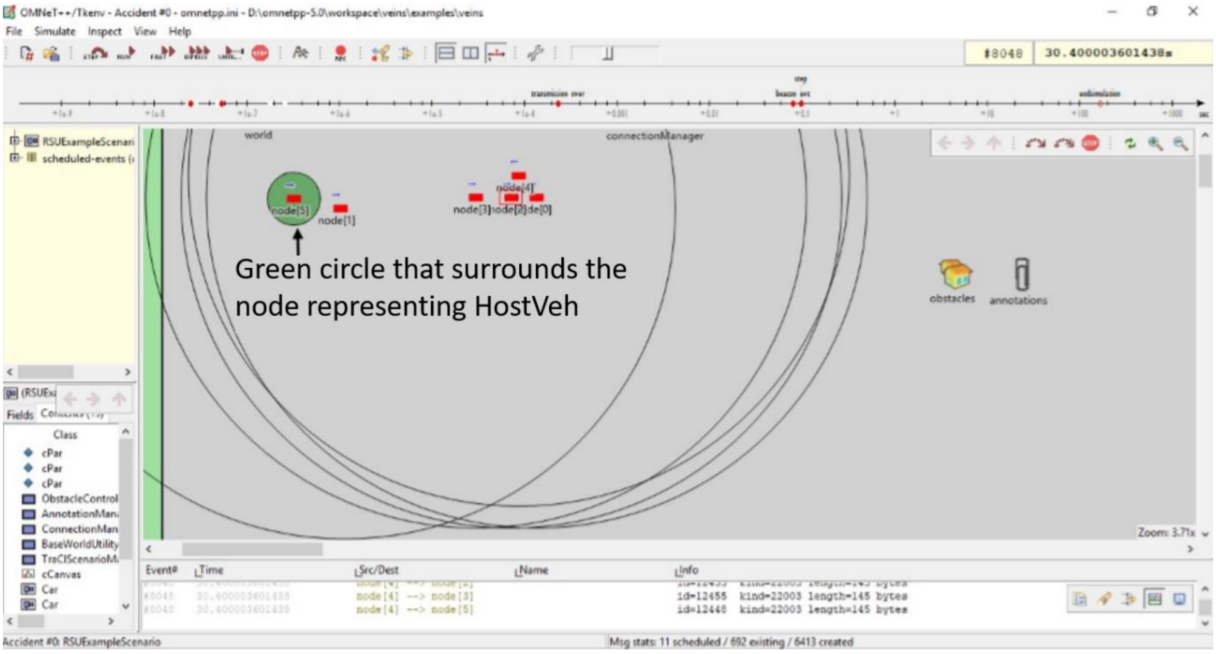
This section presents the evaluation of efficiency of the *Cooperative Road Hazard Detection Persistent Subsystem* (CRHDPS). In fact, we simulated the functionality of the two components (CDZA[4] and COD[5]) together using about ten scenarios.

However, we limit ourselves to presenting only one scenario. The simulation results of this scenario are shown in figures A10, A11 and A12. In this scenario, a HostVeh is moving from West to East. Its Route Manager detects a static obstacle on the road that corresponds to a stopped vehicle, presented by the green color, as shown by the figure A10. Since the vehicle arriving from the opposite lane is still far away (*cf.* blue vehicle in the figure A10), the HostVeh Motion Controller orders its steering unit to pass this obstacle and thus avoid a collision with this unpredictable obstacle. This is illustrated by the green circle surrounding the node representing the HostVeh in the OMNET++ simulator (*cf.* figure A10 (b)).

[4] Cooperative Dangerous Zone Alert
[5] Cooperative Obstacle Detection



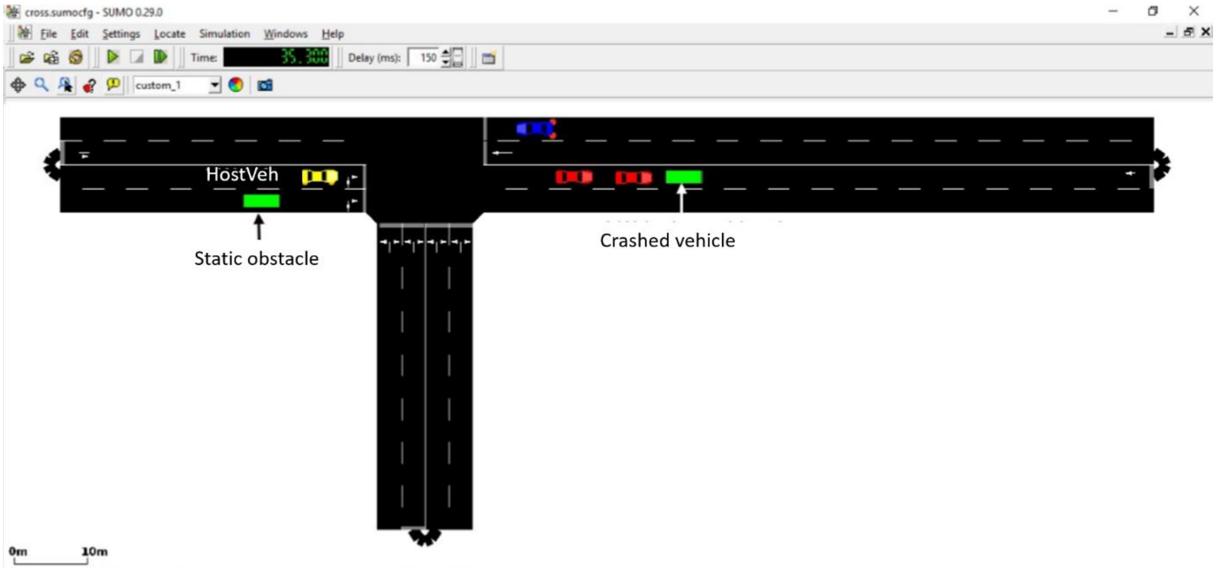
(a)



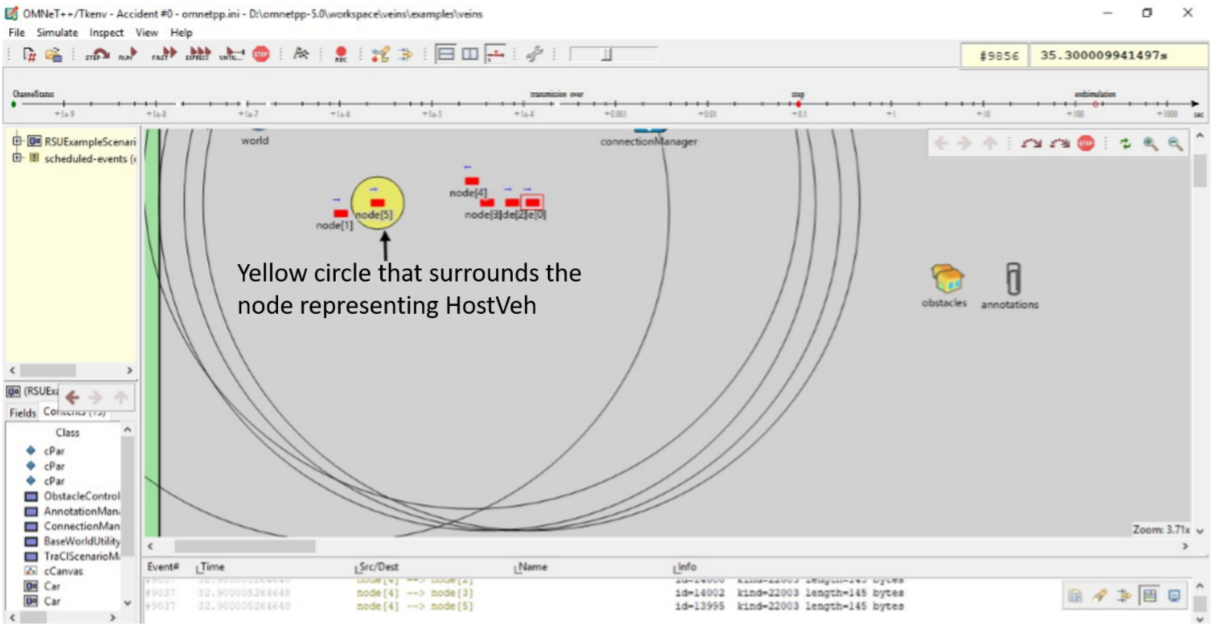
(b)

Figure A10. *Screenshot of a scenario where the CACC component is triggered when the overtaking maneuver is not allowed in the OMNET++ simulator.*

After overtaking the static obstacle, the HostVeh Situation Detector also detects a dangerous zone, *i.e.*, an accident vehicle (*cf.* green vehicle in figure A11 (a)). This crashed vehicle has created a congestion zone as the two vehicles in red are stopped before the crashed vehicle. In such a situation, the Host Vehicle Route Manager decides that the Host Vehicle is in favor of changing lanes to the South and orders his steering unit to do so. This is illustrated by the yellow circle surrounding the node representing the HostVeh in the OMNET++ simulator (*cf.* figure A11 (b)).



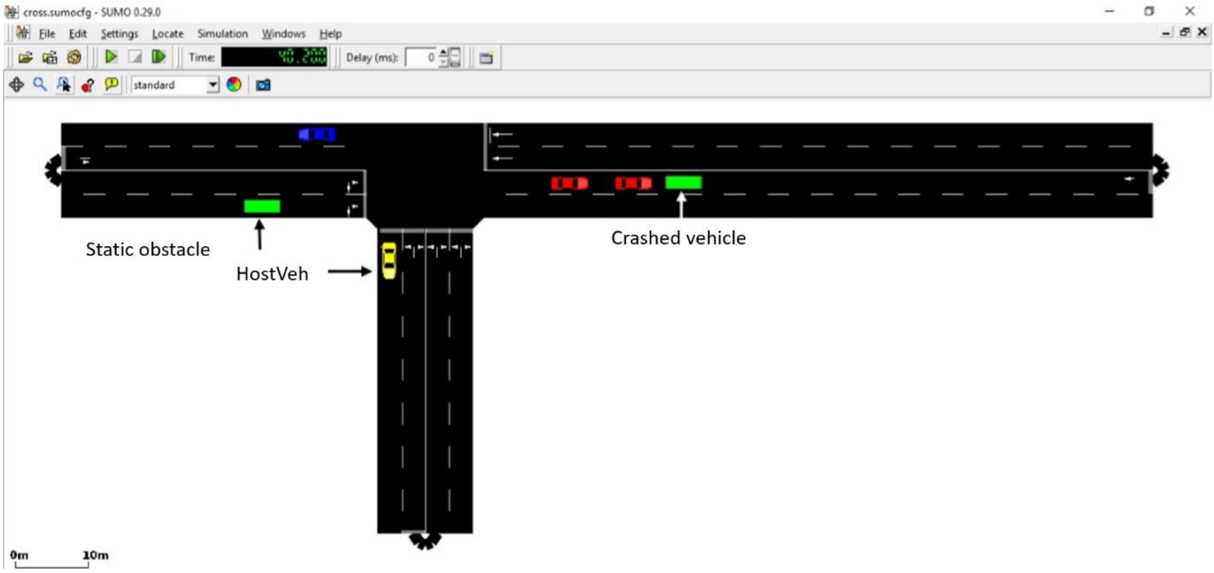
(a)



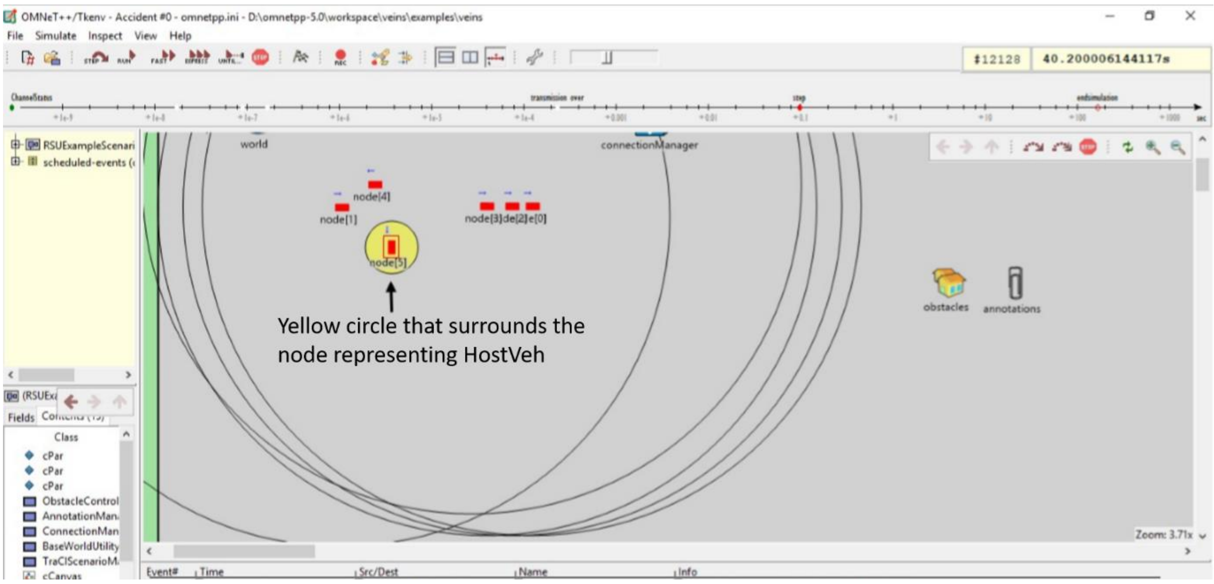
(b)

Figure A11. *Screenshots of a scenario where the HostVeh encounters a dangerous area on the road under the simulators (a) SUMO and (b) OMNET++.*

Figure A12 shows that the HostVeh has changed its route to the south to avoid congestion with the accident area.



(a)



(b)

Figure A12. *Screenshots of a scenario where the HostVeh encounters a dangerous area on the road under the simulators (a) SUMO and (b) OMNET++.*