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ORIGINAL PAPER

Addressing hazardous weather conditions on Middle East highways with smart infrastructure and connected vehicles using agent-based simulation

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Abstract
The lack of visibility due to foggy conditions is known to cause of a lot of accidents every year in the United Arab Emirates, eventually leading to fatal injuries. Yet, today's technology can help to overcome these visibility issues by providing dynamic information to the driver about the current weather and an appropriate speed limit. This paper explores four strategies, ranging from static road signs to advanced inter-vehicular communication, to better warn the drivers and make them adapt their speed depending on the weather. To evaluate the impact of each policy, agent-based simulations are designed and performed. The results show that a dynamic communication about the weather conditions, supported by either an infrastructure-to-vehicle or a vehicle-to-vehicle protocol, can reduce the probability of occurrence of accidents.

Keywords Agent-based simulation · Microscopic simulation · Traffic simulation · Foggy weather condition

1 Introduction

Based on historical records, driving in heavy fog conditions is one of the most serious causes that lead to fatal accidents on UAE roads in general and Abu Dhabi and Dubai highways in particular. For instance, on October 2015, fog has covered large areas of the UAE between 4 a.m. and 8 a.m. causing 88 accidents. Abu Dhabi police reported that on January 2015, due to heavy fog conditions, dozens of vehicles collided on the Abu Dhabi-Dubai road leaving 20 persons with minor injuries from separate cases of collisions. Soon after, on January 2016, the Ministry of Interior announced that around 23 people were injured in four accidents involving a total of 96 vehicles on the Abu Dhabi-Al Ain road (see Fig. 1).

Moreover, on February 2016, a massive pile-up involving around 40 vehicles brought traffic to a standstill on Sheikh Zayed Road, according to Dubai Police. Accidents took place on the Abu Dhabi-Dubai border due to thick fog and caused 136 accidents. The Dubai Police partially closed the E11 highway to clear the road. A summary of additional fog-related accidents on UAE roads for the period 2008–2016 is shown in Table 1 (Source: http://www.rta.aewww.rta.ae).

All these massive accidents, and several other relatively minor ones, were due to poor visibility conditions caused by dense fog. Vehicles driving at high speed suddenly enter road sectors covered by dense fog without warning and are then involved in mass collisions. Driving in bad weather in the UAE is often linked to fog, rain, or sand storms with low visibility being the common denominator. Every year, the UAE suffer pile-ups, which are typically a chain reaction. One accident occurs; sometimes just a small fender bender and following motorists cannot avoid colliding with the obstacles in front of them due to the lack of proper distance, lack of attention, or excessive speeds.

Solutions for improving road safety when drivers face poor visibility due to foggy weather conditions are multiple. In the context of our project, we consider that the major solutions are related to the application of

(i) crowd-sensing of visibility estimation and
(ii) vehicle-to-vehicle and vehicle-to-infrastructure communication (V2x).

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Fig. 1 Ninety six (96) vehicles involved in mass collision due to fog (January 2016, Sources: www.rta.ae, https://www.spiegel.de/auto/aktuell/abu-dhabi-massenkarambolagemit-100-autos-a-1072435.htmlDer Spiegel)

The participatory measures enable the diffusion of the knowledge among the car drivers, and then adapt there behaviors to the situation. However, this first solution needs to have an active action from the drivers and a communication infrastructure. We consider that introducing V2x enables to build an automatic system for managing the visibility issues participates to the global solution. Therefore, this paper focuses on this second point by providing a *study of three strategies including connected road devices and connected vehicles in order to reduce accidents in foggy weather conditions.* The first point is outside the scope of this paper. These three strategies are considered in this study in separated simulation scenarios, as well as a reference scenario:

- *No smart system:* The drivers do not have a dynamic information related to the fog situation. It is the reference scenario.
- *Smart devices:*The drivers perceive the road signs (e.g., speed limit panels) that are able to adapt their screens to reflect the foggy weather situation.
- *Onboard notifications:* Extends the previous scenario with notifications to the driver of speed limits on the vehicle's board. The notifications are sent by the smart devices.
- *Connected vehicles:* Extends the previous scenario with vehicles that are able to exchange the speed limits through vehicle-to-vehicle communication.

Table 1 Log of major fog-related road accidents across the UAE 2008–2019

	Vehicles Crashes	Injuries
March 2008	200 cars crashed due to poor visibility caused by the thick fog on Abu Dhabi-Dubai highway. 25 vehicles caught fire (see Fig. 2)	4 people died, 350 were injured
March 2009	Bus crashed into an outdoor advertising billboard on the outskirts of Ras Al Khaimah	54 labourers and a driver were injured
October 2011	32-car pile-up on the Dubai Bypass Road just before the Al Ain highway interchange	Not reported
February 2012	2 accidents near to Emirates Roundabout in Abu Dhabi	1 Asian woman was killed
February 2013	A bus and lorry collided in Al Ain's Al Arrad region	A 20-year-old emirati woman was killed, 6 other female emiratis were injured plus the bus driver
May 2013	140 crashes in the space of six hours in Dubai	Not reported
January 2014	57-car pile-up Abu Dhabi and Al Ain road	14 people were injured
January 2015	Dozens of vehicles collided on the Abu Dhabi-Dubai highway	20 people were injured
February 2016	136 accidents of the E11 near Jebel Ali	No death were reported
February 2018	44 vehicles o a major event on Sheikh Mohammed bin Rashid Road	22 people were injured
13 March 2019	3 accidents, in cluding one with 11 vehicles at Ghantoot, Abu Dhabi and Sharjah	Minor injuries
15 March 2019	205 reports of accidents in Abu Dhabi, Al Ain and Al Dhafra caused by morning fog (68 vehicles)	10 minor injuries

Fig. 2 Twenty five (25) vehicles caught fire following the accidents caused by the thick fog (March 2008, Source: www.rta.ae)

To provide accurate results, a high-resolution spatial model was established in our previous research representing the state of the traffic infrastructure and the driving population [27]. It is based on an agent-based model (ABM) that is a class of computational models for simulating the actions and interactions of autonomous agents with a view to assessing their effects on the systems as a whole [9, 26]. Many research areas, such as transportation behavior modeling [3, 12, 13, 23], need to analyze and understand the complex phenomenon of interactions between different entities. Connected and autonomous vehicles, as well as connected human beings and Internet of Things objects, will be considered as agents. The proposed ABM follows the latest advancements in the fields of agent-oriented software engineering and agent-based simulation. The Janus platform [11, 14, 15] and its associated SARL meta-model and agent programming language[1] [6, 8, 10, 29] are used for building the simulator. The source code of the simulator is published as open source code on Bitbucket.[2]

This paper is structured as follows: Sect. 2 presents several related works. The different agent behaviors for vehicles and connected objects are detailed in Sects. 3 and 4, respectively. The simulation of traffic in foggy weather condition is described and discussed in Sect. 5. Conclusions and perspectives are provided in Sect. 6.

[1] SARL: http://www.sarl.io

[2] Bitbucket source folder: https://bitbucket.org/sgalland/zayed-fogsimu

2 Related works

Several recent research works were focusing on the study of foggy weather conditions on road traffic. [5] study the effectiveness of fog warning systems in driving performance and traffic safety in heavy fog conditions. This work provides a multivariate analysis of variance for highlighting the effects of drivers' individual characteristics on driving behavior. The implemented simulator is mesoscopic and not based on agent paradigm. Authors found that On-Board Unit (OBU) had a significant impact on individual speed adjustment. Therefore, OBU will be included in short-term in our simulation scenarios and compared to the two scenarios that were described here.

Tan [33] proposes a longitudinal driving model to investigate the impact of driver risk illusions on traffic flow. This model is applied in scenario with foggy weather conditions. Linear stability analysis and numerical simulations of the proposed model are conducted, but they are not based on the agent paradigm. The comparison between the longitudinal driving model of [33] and RT-CVC [18] will be made in a dedicated paper. [20] propose a study on adaptation effects in the case of fog in relation to two longitudinal driving behaviors (Helly [19] and IDM [34]). Authors show from the experiments a significant decrease in speed and a significant increase in distance to the lead vehicle. Furthermore, the results showed that acceleration significantly decreased. The effect of fog on deceleration was not significant. These effects have also been found in our experiments. [1] propose prediction models to perform numerical fog forecasts. They couple the one-dimensional PAFOG fog model with the three-dimensional Weather Research and Forecast modeling system. The proposed model is used for implementing a road traffic warning system. These models are focusing on the fog evolution on the map and not on the traffic model itself. However, the model of [1] could be adapted and injected into our model instead of the static definition of the foggy weather area. Among several agent frameworks that are dedicated to traffic simulation, GAMA [17], MATSIM [21], and SUMO [24] are widely used, especially in EU. All of them are based on the agent paradigm with different and specific meta-models. They provide features that enable to simulate traffic flows under foggy weather conditions. However, the meta-model of SARL is considered more generic and enables the implementation of complex systems through both organizational and agent modeling paradigms. Regarding the agent paradigm and the agent environment model, SARL/Janus follows strictly the definitions and principles from [25, 30, 35]. Moreover, the SARL/Janus model enables sub-microscopic simulation of the vehicles, i.e., the simulation of the vehicle's physical components [22]. Finally, because of its design, SARL/Janus enables the distribution of the simulation over a computer network with a small effort.

3 Driver models

Two types of drivers are considered: regular and connected drivers. Both are detailed in the following sections. Section 3.3 is dedicated to the adaptation of these driver models to consider foggy weather conditions for the agent decisions.

3.1 Regular driver

The behavior of a regular driver, e.g., a driver of a non-connected vehicle, is based on the layered architecture presented in Fig. 3, which decomposes the general driver model into complementary modules. The modules used in this research are described in the following sections.

3.1.1 Path Selection module

In the "Path Selection" module, the agent chooses the route to follow to reach its goal. A sequence of daily activities, in which travel activities are involved, may be modeled and used. In this paper, routes are precalculated and provided to agents following a stochastic distribution, arising directly from the results of transport demand simulations.

3.1.2 Desired/cruise speed selection module

The choice of the desired/cruise speed is achieved by modulating the maximum speed $\dot{v}$ allowed by the regulations and expressed through road signals. Therefore, the model for trajectory and speed computation analyzes the perception of the agent to detect any change in this speed information. The agent determines also the comfort speed to pass a road curve according to (1) [32], where R is the radius of the curve.

$$V_d = \frac{102}{1 + \frac{346}{R^{1.5}}} \tag{1}$$

Therefore, $\dot{v}'$ is the desired speed after the adaptation to the trajectory (see (2)) [27].

$$\dot{v}' = \begin{cases} \theta.\min(\dot{v}, V_d) & \text{if } P(\text{change}) \geq p_{as} \\ \min(\dot{v}, V_d) & \text{otherwise} \end{cases} \tag{2}$$

$\theta \in \mathbb{R}+$ is the factor for modeling the approximate computation of a speed that is done by a human. Each driver agent has the choice to adapt or not its speed to the road trajectory. This fact is modeled with a probability value that should be greater than or equal to p_{as}.

3.1.3 Collision Avoidance module with longitudinal driving model

The "Collision Avoidance" module is responsible for issuing the agent influences [25]—or actions—for the driver agent to the simulated vehicle in the form of vehicle acceleration. To compute the vehicle acceleration, several models were proposed in the literature. They are named "longitudinal driving models" or "car-following models." In this research, three models are used:

(i) Reaction Time-based Collaborative Velocity Control (RT-CVC) [18];
(ii) Intelligent Driver Model (IDM) [34];
(iii) Intelligent Driver Model Plus (IDM+) [31].

A preliminary comparison is provided by [28]. Other longitudinal driving models can be found in the literature [2, 4, 16].

RT-CVC model [18] is developed to deal with the occupancy of a conflict zone. From the point of view of car following, the conflict zone could be considered as a location on road before the following vehicle. This model is implemented as a control algorithm for real autonomous cars [18]. The acceleration a_r of a vehicle is provided by (3). This acceleration is used by the following vehicle for braking or acceleration during the next simulation step Δt.

$$a_r = \frac{b_f \tau - 2v_f \pm 2b_f \sqrt{\dfrac{b_f b_l \tau^2 + 4b_l v_f \tau + 4v_l^2 - 8b_l s}{4b_f b_l}}}{2\tau} \tag{3}$$

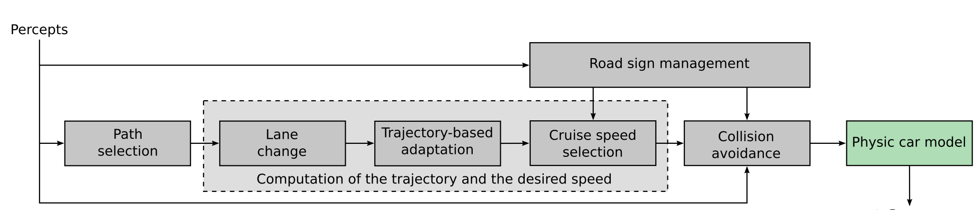


Fig. 3 General architecture of the driver behaviors [27]

s is the distance between the two successive vehicles. If s becomes lower to the minimal safety distance for breaking s_0, the vehicle starts its emergency braking behavior. v_f and v_l are the current velocity of the follower and leader, respectively. b_f and b_l are the maximum decelerations of the follower and the leader. And τ is the reaction time of the driver. In some unusual cases, the bumper-to-bumper distance may be less than the minimal headway s_0. Consequently, the final control equation is given by (4) and (5).

$$a_r = \begin{cases} b_f & \text{if } s < 0 \\ \dfrac{b_f\tau - 2v_f - 2b_f a^*}{2\tau} & \text{if } s \geq 0 \end{cases} \tag{4}$$

$$a^* = \sqrt{\frac{b_f b_l \tau^2 + 4b_l v_f \tau + 4v_l^2 - 8b_l s}{4b_f b_l}} \tag{5}$$

IDM is a time-continuous car following model for the simulation of freeways and urban traffic [34]. It describes the dynamic of the positions and velocities of a vehicle, as defined in (6) and (7).

$$\frac{dv}{dt} = a \cdot \left[1 - \left(\frac{v_\alpha}{v_0}\right)^4 - \left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s}\right)^2\right] \tag{6}$$

$$s^*(v_\alpha, \Delta v_\alpha) = s + v_\alpha T + \frac{v_\alpha \Delta v_\alpha}{2\sqrt{ab}} \tag{7}$$

a is the comfortable acceleration, v_α is the current speed for the vehicle α, v_0 is the desired speed, and s_0 is the minimum headway (at standstill). T is the desired time headway. Δv_α is the speed difference with the leader. s is the current distance headway, and b is the comfortable deceleration. IDM shows realistic shock wave patterns, but has a macroscopic capacity of just below 1900 veh/h. In order to reach a reasonable capacity, the desired time headway needs to be lowered to unreasonable values.

IDM+ is a variant of IDM in order to focus on the traffic flow stability [31]. To this end, a minimization over the free-flow and the interaction terms of IDM equations is defined, similarly to models based on [19] and [16], as described in (8) and (7).

$$\frac{dv}{dt} = a \cdot \min\left[1 - \left(\frac{v_\alpha}{v_0}\right)^4, 1 - \left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s}\right)^2\right] \tag{8}$$

By explicitly separating the free-flow and interaction terms, the equilibrium fundamental diagram of the IDM changes from a smooth topped-off shape to a triangular shape. Unstable behavior in the IDM is largely dependant on s^* as this includes the exaggerated response to speed difference and deviation from the equilibrium headway. Strong deceleration triggering traffic flow instability occurs with $s^* >> s$. This still holds for the IDM+ as long as $v \leq v_0$. The maximum acceleration difference is equal to a.

3.2 Connected driver

A connected vehicle is a vehicle that is equipped with communication devices and usually with a wireless local area network. This allows the car to share network access with other devices both inside as well as outside the vehicle. Often, the vehicle is also outfitted with special technologies that tap into the wireless network and provide additional benefits to the driver.

The behavior of the driver agent is updated to include the support of the different types of communications (vehicle-to-vehicle and infrastructure-to-vehicle). In essence, the communication model is based on the communication capabilities of the agents and based on the messages that they could exchange. As illustrated by Fig. 4, two new modules (in red) have been added into the general architecture of the driver agents, compared to the architecture in Fig. 3.

3.2.1 Communication Receiver module

The "Communication Receiver" module is in charge of receiving and filtering the messages that are received by the agent. Its role is to extract any relevant data from the messages in order to update the knowledge of the agent. The messages that are considered in this project are as follows:

- *Speed limit:* This message contains a speed limit that should not be overtaken by the receiving agent. When an agent receives an occurrence of this message, it is updating its knowledge about the maximal speed that it could select.
- *Dangerous situation:* This message contains the position and the type (accident, etc.) of a dangerous situation. When an agent receives an occurrence of this message, it includes the situation as a candidate for collision avoidance.

3.2.2 Information Emitter module

The "Information Emitter" module emits messages into the system to set up a communication between the agents. The module is based on the algorithm in Algorithm 1.

The time t' at which the messages should be received is randomly computed into the time windows $[0; \rho]$, where ρ is a parameter of the agent model, i.e., each agent could have a different value for ρ. The agent a emits a `SpeedLimit` message according to its probability p_{smax}. This message contains the known maximal speed limit $\dot{v}_{smax}$, the timestamp t', and the current position pos_a of the agent a. If

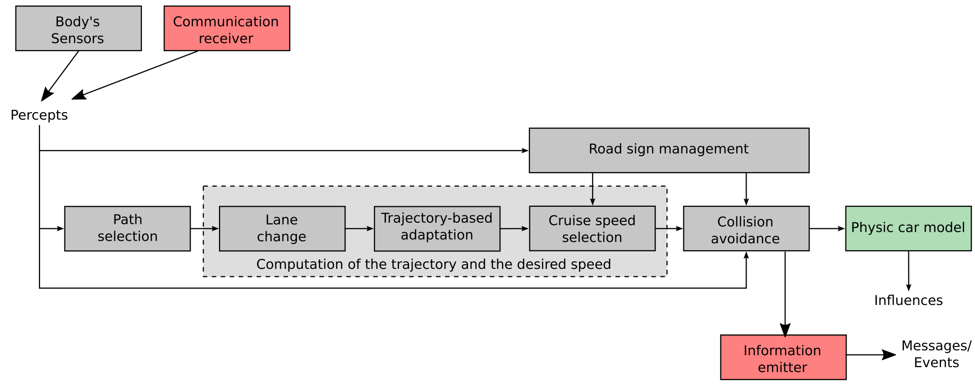


Fig. 4 General architecture of the connected car driver behaviors [27]

Algorithm 1 Information Emitter Module.

$t' \leftarrow t + random([0..\rho])$
if $P(p \leq p_{smax})$ **then**
  emit SpeedLimit event with $(\dot{v}_{smax}, t', pos_a)$
else
  if $pos_{dang} \neq \emptyset$ and $P(p \leq p_{dang})$ **then**
    emit DangerousSituation event with (pos_{dang}, t', pos_a)
  end if
end if

the agent a knows the position pos_{dang} of a dangerous situation, it emits with probability p_{dang} a message of type `DangerousSituation` with pos_{dang}, the timestamp t', and its current position pos_a.

3.3 Support of the foggy weather conditions

Fog is among the most influential factors that impact road traffic safety. Foggy weather conditions were included into the simulation in two different modules.

First, fog has a real presence in the simulated agent environment. Therefore, it is included into the agent environment's model itself, that is, the data structure from which agents' perceptions are computed. Consequently, the agent becomes able to perceive fog by extracting `FogWall` objects from the collection of objects that it is perceived around. The position and distance to this wall could be used by the driver agent to determine its best speed.

Second, assuming that the driver agents are able to perceive fog as explained above, the driving behavior should be adapted by considering the fog wall as a possible obstacle. Consequently, only the *Collision Avoidance* module is impacted by the foggy weather situation in our driving behavior architecture. In this case, the "Collision Avoidance" module select the *most dangerous* object between a car to follow and the fog wall. Dangerousity of the objects is based on the distances to these objects.

4 Road signs behaviors

Vehicle-to-Infrastructure (V2I) communication is part of Intelligent Transportation Systems (ITS) that is supported in our study. V2I technologies capture vehicle-generated traffic data, wirelessly providing information such as advisories from the infrastructure to the vehicle that inform the driver of safety, mobility, or environment-related conditions [7]

The behavior of an infrastructure component is directly supported by dedicated agents and illustrated by the diagram in Fig. 5. The "Data Extraction" module is dedicated to the sensing of the environment and the extraction of raw data. The role of this module is to specify the field of perception of the sensor. The role of the "Data Filtering" module is to discard the objects from the extracted data set that are not relevant to the behavior of the infrastructure component. The "State Change Computation" module is the key module of the infrastructure agent. Its role is to update the variables in the current object's state Δ according to the filtered data. For example, the state of a traffic light may be a value in

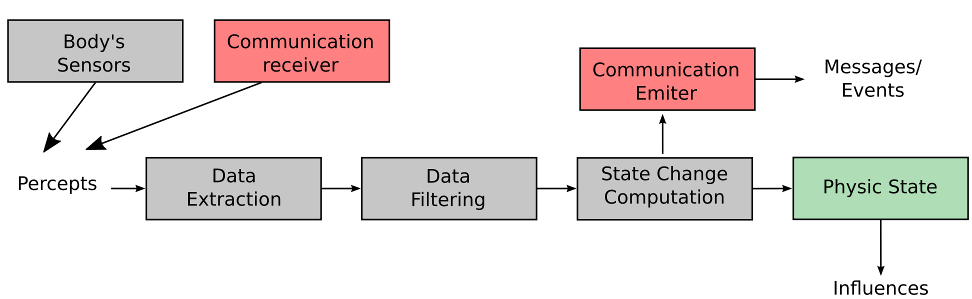


Fig. 5 General architecture of the road signs' behavior, adapted from [27]

the set {Pass, Prepare-to-stop, Stop} that is selected according to the state of the traffic around. The "Physic State" module is in charge of transforming the state Δ of the infrastructure component from actions provided by the simulated agents to change the physical description of this component in the agent environment. For example, the module for a traffic light may transform the state value `Pass` to the green color, Prepare-to-stop to orange, and Stop to red. The "Communication Emitter" module is in charge to prepare any communication with other infrastructure components (I2I), the network (I2N), or vehicles (I2V). As for driver agents, the communication is supported by agent messages.

4.1 Smart speed limit panel

In the context of this research, a single type of infrastructure agent is modeled and implemented: smart speed limit panel. The general behavior of this agent is to show up the current speed limit at the location of the panel. This speed limit is computed according to (9) [27], where $\dot{v}_{legal}$ is the legal speed limit (constant into the agent behavior) and $\dot{v}_{percept}$ is the speed limit, that is, the result of the data extracted by the agent.

$$\dot{v}_{max} = \min\left(\dot{v}_{legal}, \dot{v}_{percept}\right) \quad (9)$$

$$\dot{v}_{percept} = \min\left(\dot{v}_{v2i}, \dot{v}_{fog}\right) \quad (10)$$

According to (10), the perceived speed limit $\dot{v}_{percept}$ depends on two inputs:

- The speed limit $\dot{v}_{v2i}$ that is embedded into a `SpeedLimit` message, received by the agent; and
- The fog sensor that provides information about the fog density at the place of the panel. This density is used for computing the expected speed limit $\dot{v}_{fog}$ in the foggy weather condition (see (11)) [27]:

$$\dot{v}_{fog} = \begin{cases} +\infty & \text{if no fog around} \\ \dfrac{d_{fog}.\dot{v}_{legal}}{m_{fog}} & \text{if fog} \end{cases} \quad (11)$$

where $d_{fog} \in \mathbb{R}+$ is the current visibility distance into the fog (representation of the fog's density), and $m_{fog} \leq d_{fog}$ is the maximal visibility distance into the fog under which the fog's impact on the traffic exists.

Finally, the speed $\dot{v}_{max}$ is displayed on the panel and sent via a communication channel to the neighbor objects (vehicles or other speed limit panels).

5 Application to highway under foggy weather situation

In this section, the architecture and the models that are described in the previous sections are applied on the simulation of four scenarios for highways in the United Arab Emirates in foggy weather situation.

5.1 Environment description

Regardless of the simulation scenario, the agent environment must be defined for enabling the comparison of the results. The selected environment is *a two-lane highway of 10 km long, without exit, entry, or interchange ramps*. This portion is a part of the E11 highway that is located in the United Arab Emirates, as illustrated by Fig. 6.

The vehicles are injected into the simulation at the red mark on the west part of the highway (vehicles follow the west-to-east direction). A fog zone is represented and approximated by a circle. Therefore, the fog circle is centered on the yellow mark, and the radius of the fog area will be of 600 m. Additionally, the density of the fog is represented by the visibility distance inside this fog area: 40 m.

5.2 Generation of vehicles

Vehicles are generated in the simulation with a uniform stochastic law of 7200 vehicles per hour, with the maximum number of generated vehicles set to 1000. This generation rate was selected for producing a flow of vehicles that has a similar density to those observed on the highway in the UAE and illustrated by the population evolution obtained on

Fig. 6 OSM representation (top) of a portion of the E11 highway (United Arab Emirates). The bottom part is the ESRI shape representation of this highway, used for simulation experiments

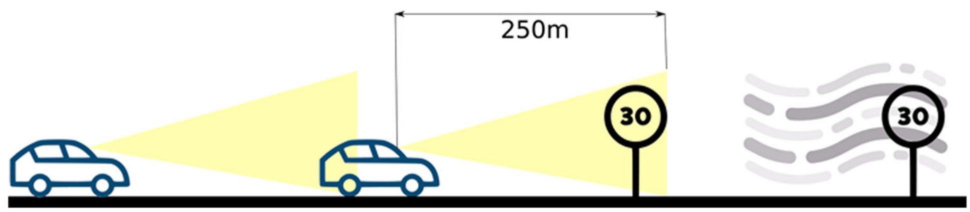


Fig. 7 Scenario 1 includes neither communication between the infrastructure and the vehicles, nor between the vehicles

Fig. 11. When it is created in the simulation, a vehicle must be assigned to a lane of the initial road segment following a linear stochastic law with a slope of −1. The initial speed of a vehicle is computed with a Gaussian law of average value given by (12) and range $[s_m; s_x]$, where s_m is the minimum speed value, s_x the maximum speed value, and i is the lane index.

$$s_m + i\frac{s_x - s_m}{L} \tag{12}$$

Regardless of the initial speed that is assigned to a vehicle, the initial acceleration is equal to 0 $m.s^{-2}$.

5.3 Scenario 1: highway without communication

In this scenario, the drivers do not have a dynamic information related to the fog situation. This scenario serves as the reference in the analysis and discussions related to the results.

Figure 7 shows a simplified view of scenario 1. Speed limit panels are regular panels, i.e., they are neither smart nor connected. The car drivers perceive the objects in front of their car with a maximum distance of 250 m. The general driver behavior is defined in Sect. 3. This general behavior is adapted to this scenario at the following points:

- The preferred cruise speed selected by the driver is the one at which the vehicle is created by the system. It is close to the legal speed limit, more or less an approximation factor.
- The safety distance that is assumed by the driver to the front vehicle is randomly selected in the range intervals given in Table 2.
- *The driver does not try to change lane.*

Inter-vehicle distance is the distance between the current vehicle and the leading vehicle. The safety distance is the minimal inter-vehicle distance under which it is assumed to be hard to avoid a collision with the front car. The safety distance sd is evaluated by (13), where γ_r is the reaction duration in seconds of the driver (usually 1 s), and γ_s is the expected time for stopping the vehicle in case of emergency (usually 5 s). $\dot{v}$ is the current speed of the vehicle (km/h). α is an approximation factor that is usually a constant.

$$sd = \alpha\,(\gamma_r + \gamma_s)\,\frac{1000\dot{v}}{3600} \tag{13}$$

Table 2 shows the application of (13) on standard speed ranges, with $\alpha = 1$.

5.4 Scenario 2: highway with smart infrastructure and I2I communication

In this scenario, the drivers are informed by road signs about a foggy weather situation. This information is not done by communication, but by visual perception of the driver.

Figure 8 shows a simplified view of scenario 2. Speed limit panels are smart and connected to the other speed limit panels. The maximum communication range of the smart panels is 2500 m. Because of this coverage range, road sign panels are put every 2 km along the road. They are able to adapt their display by showing the best speed limit in the current weather conditions. The behavior of the smart panels is defined in Listing 1 in the Appendix. It corresponds to the event handler `on SmartPanelBehavior` that defines the general behavior of the smart panel. When the panel detects fog, i.e., it is located in a foggy weather zone, it assumes that the maximum speed for a vehicle is the result of (14). At the same time, the panel broadcasts a communication message to the neighbor panels with its position.

$$speedLimitInFog = \frac{\sqrt{62500\gamma_r^2\mu^2 + 12960\mu \times visibilityInFog} - 250\gamma_r\mu}{7.2} \tag{14}$$

Table 2 Safety distances according to the vehicle speed, $\alpha = 1$

Vehicle speed (km/h)	Safety distance (m)
[0; 30)	[1; 50]
[30; 50)	[50; 85]
[50; 90)	[85; 150]
[90; 110)	[150; 185]
[110; 130)	[185; 215]
[130; +∞)	[215; 250]

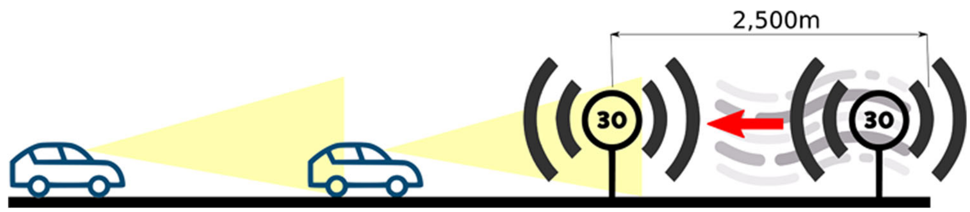


Fig. 8 Scenario 2 includes I2I communication between the infrastructure components

The computation of the maximal speed in a foggy area in order to avoid collision is based on the visibility distance in the fog and the stopping distance, that is, the sum of the reaction distance and the braking distance.[3] γ_r is the reaction duration in seconds of the driver. μ is the coefficient of friction, approx. 0.8 on dry asphalt and 0.1 on ice.

When the smart speed limit panel is not in the fog zone, it may have two different behaviors. First, if it does not have received an message related the foggy weather condition or the message is related to a too far fog zone (distance greater than θ_i meters), it displays the legal speed limit. Second, if such a message was received within a distance lower than or equal to θ_i meters, it displays an interpolated speed between the $speedLimitInFog$ and the legal speed limit according to the distance to the initial fog source. The function `normalize` applies a normalization rule that approximates to the closest lower well-known speed, such as {0, 30, 50, 70, 90, 110, 130} in France.

5.5 Scenario 3: highway with I2X communication

In scenario 3, the previous scenario is extended with I2V communication: the vehicles are notified on-board by the infrastructure about the foggy weather situation (infrastructure to vehicle communication).

Figure 9 shows a simplified view of scenario 3. Speed limit panels emit signals to the vehicles in addition to the signals that are emitted to the other smart panels. The maximum communication range of the smart panels to send messages to vehicles is 1000 m.

The infrastructure definition is extended to emit specific I2V signals to the connected vehicles. Listing 2 in the appendix redefines the function `emitI2Xsignals` in order to emit the I2I fog detection signals to the other smart panels and the I2V fog detection signals to the connected vehicles.

The `I2VFogConditionDetected` signal is emitted at a given rate κ, which is the number of signals to be emitted per second. The `I2VFogConditionDetected`signal contains the following data:

- `fogPosition`: the position of the first smart panel that has detected the foggy weather condition;
- `signalSourcePosition`: the position of the panel that emits the signal;
- `speedLimit`: the speed limit that is computed in order to avoid collision into the fog;
- `speedLimitOnPanel`: the speed limit that is displayed on the road sign that emits the signal.

The driver behavior in scenarios 1 and 2 is extended. In order to support the receiving of I2V communication messages, only the “Communication Receiver” module should be adapted. In this scenario, this module extracts information about the foggy weather condition when it receives a `I2VFogConditionDetected` message. This information is used for updating the desired/cruise speed of the vehicle.

Algorithm 2 Algorithm of the connected car with I2V communication.

if I2VFogConditionDetected is received **then**
  $signalSourcePosition \leftarrow$ from I2VFogConditionDetected event
  $speedLimitOnPanel \leftarrow$ from I2VFogConditionDetected event
  $d \leftarrow distance(position, signalSourcePosition)$
  if $d \leq \theta_{iv}$ **then**
    $foggySpeedLimit \leftarrow speedLimitOnPanel$
  else
    $foggySpeedLimit \leftarrow +\infty$
  end if
end if
$computeCruiseSpeed \leftarrow \min(foggySpeedLimit, legalSpeedLimit)$

In Algorithm 2, the driver agent determines the minimum speed limit that is provided through the I2V communication from the smart speed limit panel below a distance of θ_{iv} meters (i.e., the maximal I2V communication range). The speed limit that is notified to the driver is the one displayed on the smart speed limit panel that is the source of the I2V signal.

5.6 Scenario 4: highway with V2V communication

In this scenario, the drivers are notified through a local communication between the vehicles.

[3] Source: https://korkortonline.se/en/theory/reaction-braking-stopping/

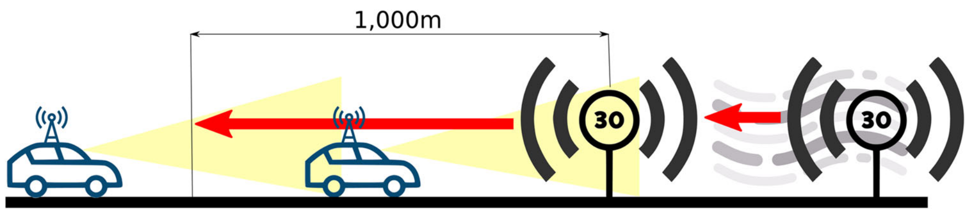


Fig. 9 Scenario 3 includes I2V communication between the infrastructure and the vehicles in addition to the I2I communication

Figure 10 shows a simplified view of scenario 4. Vehicles are equipped with on-board devices that permit to exchange V2V signals between the vehicles. The maximum communication range of vehicles is 400 m.

The driver behavior of scenario 3 is extended. To support the V2V communication, the "Communication Emitter" module should be implemented. In this scenario, this module emits `FogConditionDetected` messages that contain all information related to the known foggy weather condition.

Algorithm 3 Algorithm of the connected car with I2V communication.

if V2VFogConditionDetected is received **then**
  $signalSourcePosition \leftarrow$ from V2VFogConditionDetected event
  $speedLimitForAheadCar \leftarrow$ from V2VFogCondition Detected event
  $d \leftarrow distance(position, signalSourcePosition)$
  if $d \leq \theta_{vv}$ **then**
    $foggySpeedLimitFromOtherVehicles \leftarrow speedLimitForAheadCar$
  else
    $foggySpeedLimitFromOtherVehicles \leftarrow +\infty$
  end if
end if
if $foggySpeedLimitFromOtherVehicles \neq \emptyset$ **then**
  emit V2VFogConditionDetected event with:
  $fogPosition \leftarrow fogPosition$ in V2VFogConditionDetected
  $signalSourcePosition \leftarrow position$
  $speedLimit \leftarrow speedLimit$ in V2VFogConditionDetected
  $speedLimitForAheadCar \leftarrow$ min(
  [4] $foggySpeedLimitFromOtherVehicles$,
  [4] $foggySpeedLimit, legalSpeedLimit)$
end if

In Algorithm 3, the driver agent saves any information related to a detected foggy weather situation. When such information is available, it emits a V2V communication message with this information.

5.7 Results and discussion

We have run one hundred different experiments for each scenario and each type of the considered longitudinal model (RT-CVC, IDM and IDM+). Figure 11 shows the evolution of the population during the simulation.

As expected, the number of vehicles increases and stabilizes due to the interaction among the vehicles that limit their speeds. The RT-CVC model enables all vehicles (1000 vehicles are injected into the simulation) to pass through the highway section sooner than the IDM and IDM+ models. We could conclude that the RT-CVC model generates more fluid flows.

Figure 12 illustrates the evolution of the vehicles' speeds, whatever the position of the vehicles on the road (inside or outside the fog). For the RT-CVC model, three different stages could be shown. The average speed increases because none of the vehicles has encountered the foggy weather situation. Then, around time 500, the vehicles start to enter into the fog, that has the consequence to decrease the average speed and make it stable until all vehicles have been entered into the fog. Average speed increases again at the end of the simulation because the drivers accelerate after exiting from the fog. The speed profiles generated by the IDM and IDM+ models show two stages: the decrease of the average speed, followed by a stage during which the average speed is stable. Congestion in fog appears around time 500, the profiles of three models show an important decrease of the slopes at this time. Figure 13 shows the average speed of the vehicles when they are inside the foggy weather zone. Its speed value is stable around 17 $m.s^{-1}$ that corresponds to the maximal speed to reach to be safe with a maximum perception distance of 40 m. The higher values at the beginning and at the end of the simulation are explained by the small number of vehicles into the simulation. Therefore, the individual impact of each on the average speed is increasing. The drivers are accelerating into the fog because they are perceiving the end

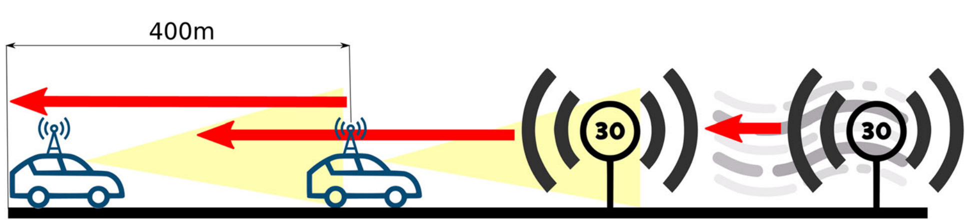
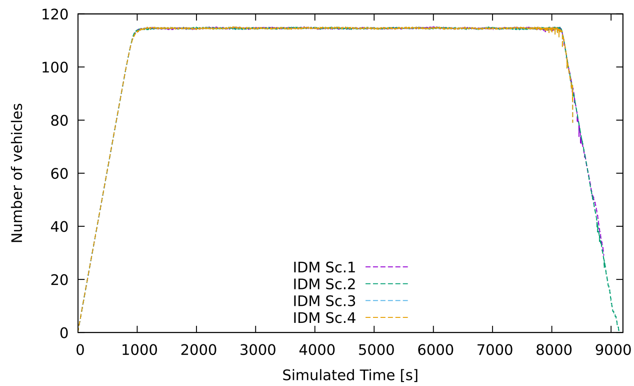
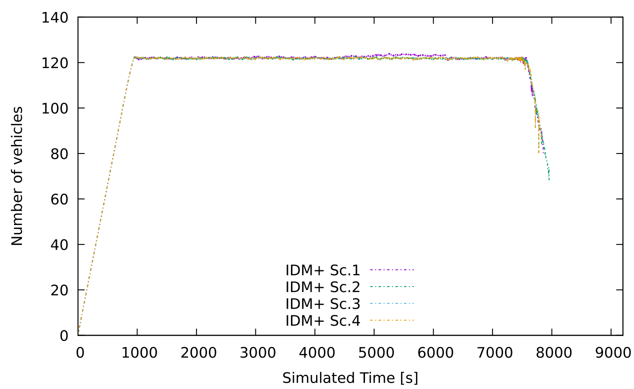


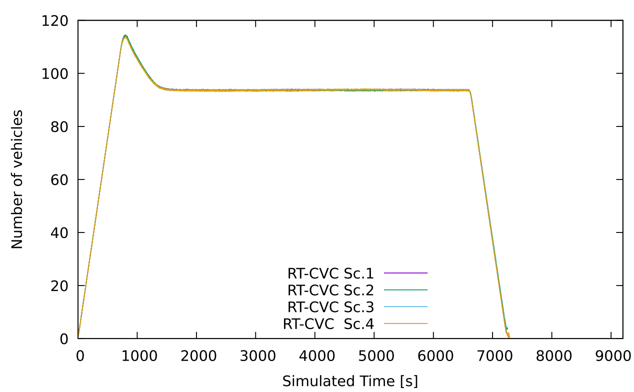
Fig. 10 Scenario 4 includes V2V communication between the vehicles in addition to the I2I and I2V communication



(a) IDM

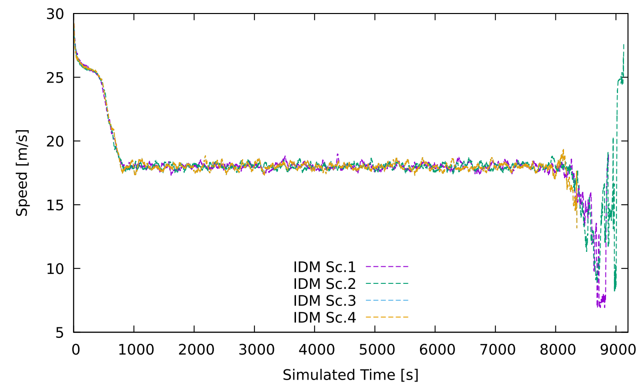


(b) IDM+

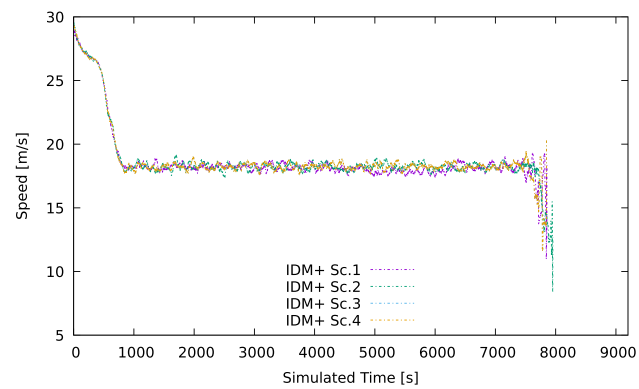


(c) RT-CVC

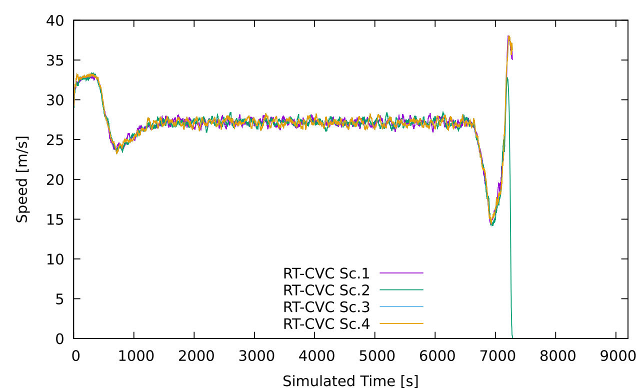
Fig. 11 Evolution of the population of cars on the highway over the simulated time



(a) IDM



(b) IDM+



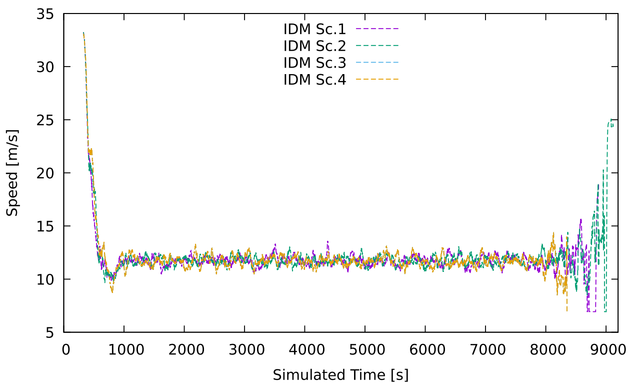
(c) RT-CVC

Fig. 12 Average speed of the simulated vehicles over the simulated time into the entire road network

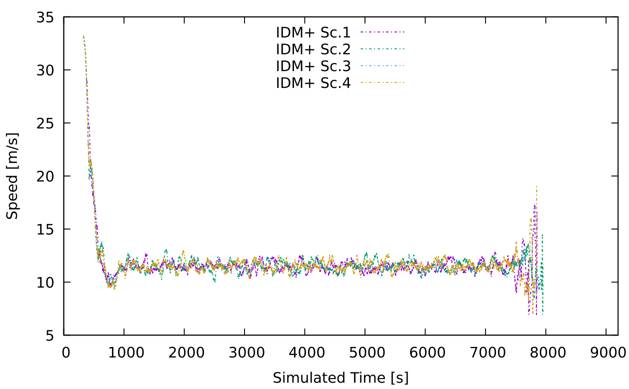
of the fog wall, even if they are still physically into the fog area.

One of the notable differences between the scenarios is the travel duration that is more important for IDM and IDM+ than RT-CVC. Figure 14 provides the simulation results related to the travel time of the vehicles. The fact that the vehicles adapt their speeds due to the connected speed limit panels could be seen with slower vehicles, those with the highest travel times, shifted in time. Additionally, for the four scenarios of a longitudinal model, we could show local increases of the travel duration that are shifted in time for the scenarios: the more the scenario includes connected devices, the more the travel duration increase comes early in time.

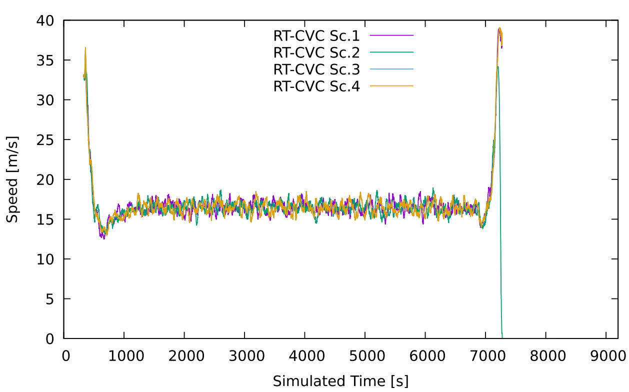
The probability to observe accidents, i.e., a vehicle that is colliding with another vehicle, depends on the reaction time and the perception distance of the vehicles. The number



(a) IDM

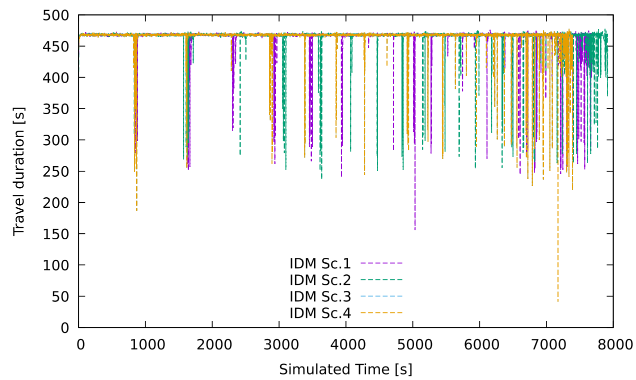


(b) IDM+

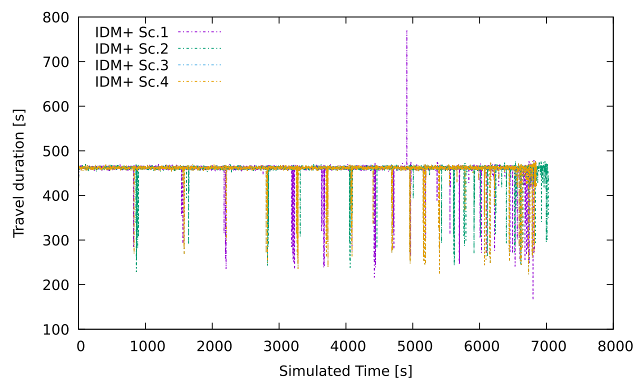


(c) RT-CVC

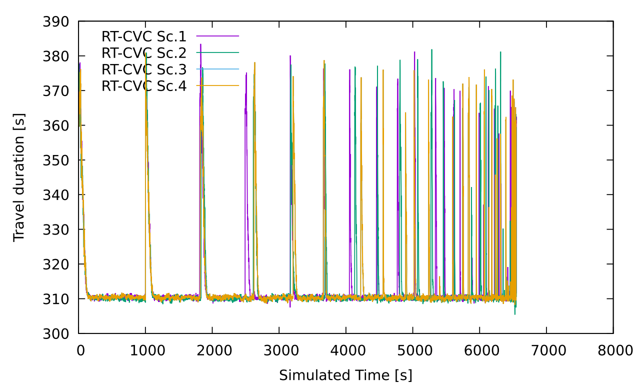
Fig. 13 Average speed of the simulated vehicles over the simulated time into the foggy weather zone



(a) IDM



(b) IDM+



(c) RT-CVC

Fig. 14 Average duration for the vehicles to traverse the experimental area

of measured accidents for IDM and IDM+ follows $P(0.27)$ whatever IDM or IDM+ is used. The number of measured accidents when all agents are using RT-CVC tends to be 0. The RT-CVC driving behavior model is designed to be efficient in extreme cases to be deployed in real autonomous vehicles. The previous results were obtained with the constants in the equations having fixed unique values, e.g., the reaction time $\gamma_r = 1$, for all agents. When the reaction time γ_r is randomly selected by each agent in [0.5; 1.5], then the average probability to have accidents is given by Table 3 for IDM and IDM+ models. The RT-CVC model does not generate a significant number of accidents again. The difference between these accident probabilities could be explained by the fact that the vehicles are slowing down early in ITS-based scenario due to the smart speed limit panels and the connected vehicles, and the inter-vehicular distances, along with the relative speeds that tend to be in the safe value ranges.

Table 3 Average probability to generate accidents when simulating the 4 scenarios with a random driver reaction time in [0.5; 1.5]

Scenario 1	Scenario 2	Scenario 3	Scenario 4
0.27	0.23	0.21	0.20

Experiments are done on a computer with processor Intel Bi-Xeon Platinum 8168 2.7 GHz and 3.7 GHz Turbo, with 512 Gb of DDR4 LRDIMM ECC (2, 666 MHz) of memory, running Linux Ubuntu 16.02, SARL 0.10 (http://www.sarl.io) and Open JDK 1.8. Figure 15 provides the execution time for each simulation step of 0.5 s simulated time.

In general, the execution performance of the model is stable and low (0.08 milliseconds for simulating the microscopic perception, behaviors, and actions for around 120 agents that is the average number of agents alive during a simulation step). Four phases could be observed. First, the number of vehicles that are generated in the simulation increases. It causes the execution time to increase also. When the number of vehicles into the simulation becomes stable, the execution of the simulation decreases due to the usage of hash tables and data binary trees for storing the perception and action lists. The third stage is harder to explain. Indeed, the linear increasing of the execution time could be explained by the types of internal data structures into the simulator or the management of the threads by the Janus framework. More investigation is needed on that point. Finally, the decreasing of the execution time reflects the fact that vehicles are going outside the simulation environment.

6 Conclusion and future works

This paper studies four scenarios to reduce the number of accidents on highways due to poor visibility conditions and proposes a model for simulating them. These scenarios rely on four different levels of communication about the weather conditions and the speed limits: no dynamic information, information provided by dynamic road signs, dynamic information transmitted by the infrastructure and displayed by an on-board device, and information exchanged with vehicle-to-vehicle communication. The information is then used by the driver to adapt its behavior by adjusting the speed of the vehicle. Simulations are then performed to identify the potential benefits and drawbacks of each solution. These simulations rely on 3 different car-following models: IDM and IDM+ to reproduce the human behavior and RT-CVC which is more oriented toward the simulation of vehicles equipped with an adaptive cruise control.

From the simulation results, it can be observed that, with RT-CVC, the probability of generating collisions tends to zero, regardless of the simulation scenario; however, with

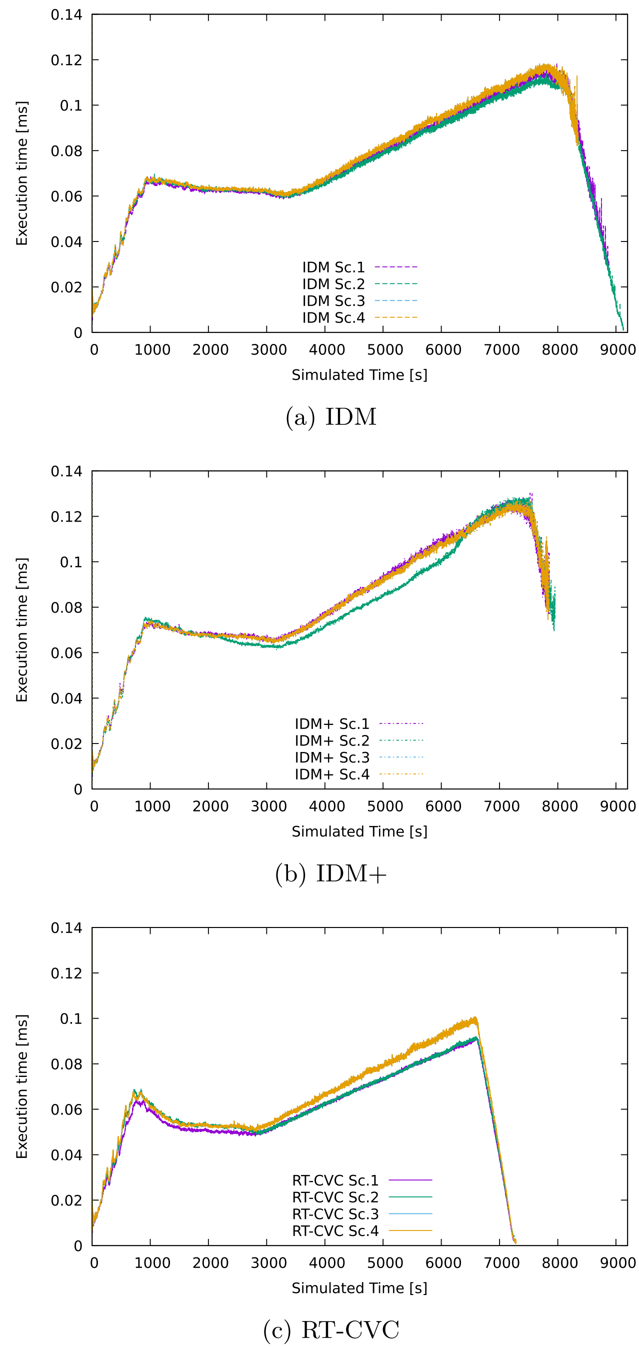


Fig. 15 Average duration of the execution of a single simulation step, which includes the computation of the agent perceptions, the execution of the agent behavior, and the application of the agent actions

IDM and IDM+, the probability of generating accidents changes depending on the scenario. The average probabilities to generate accidents are, respectively, 0.27, 0.23, 0.21, and 0.20 for each one of the scenarios (Table 3). Thus, a decrease in the probability of generating accidents can be observed when using more dynamic communication solutions. It can also be noted that using RT-CVC for longitudinal control, in addition to the decrease in the number of accidents, produces a more fluid traffic (with a higher average speed and a reduction of the travel time of the vehicles).

Like all models that cover real-world transportation problems, the simulation model proposed in this paper *(i)* requires a large amount of detailed and accurate input data, including the agent's socio-economic attributes and road network information, and *(ii)* has scalability issues that still need to be solved.

Indeed, it is necessary to consider a sufficiently large region to evaluate the impact of foggy weather conditions at this scale. Apart from scalability issues, future research will focus on enhancing the interaction between agents by including more realistic communication models and include them into a systematic comparison study.

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Author Contributions Fatma Outay and Stéphane Galland have jointly proposed the agent-based model and the corresponding behaviors. Stéphane Galland has implemented the agent-based simulator with the SARL agent programming language. Abdeljalil Abbas-Turki has implemented the RT-CVC model. Thomas Martinet has implemented the agent-based simulator and the associated webservices for providing the data collection. All authors have contributed to the discussions.

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Code availability Source code of the simulator is published as open source code on Bitbucket platform: https://bitbucket.org/sgalland/zayed-fogsimu

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

Appendix. Listings

```
on SmartPanelBehavior {
  if (panel.inFog) {
    panel.display(speedLimitInFog)
    emitI2Xsignals(panel.position, speedLimitInFog,
                   speedLimitInFog)
  } else if (I2IFogConditionDetected ≠ ∅) {
    var ds = distance(panel.position,
                 I2IFogConditionDetected
                 .signalSourcePosition)
    if (ds ≤ θ_i) {
      var sif = I2IFogConditionDetected.speedLimit
      var fp = I2IFogConditionDetected.fogPosition
      var df = distance(panel.position, fp)
      var α = df / θ_i
      var α_c = min(1, α)
      var β = (legalSpeedLimit − sif).abs ∗ α_c
      var s = min(legalSpeedLimit, sif) + β
      s = s.normalize
      panel.display(s)
      if (s < legalSpeedLimit) {
        emitI2Xsignals(fp, sif, s)
      }
    } else {
      panel.display(legalSpeedLimit)
    }
  }
}
def emitI2Xsignals(fogPos : Point2d, sif : double,
                   sp : double) {
  emit(new I2IFogConditionDetected => {
    fogPosition = fogPos;
    signalSourcePosition = panel.position;
    speedLimit = sif
  })
}
```

Listing 1 Algorithm of the smart speed limit panels, using the SARL syntax

```
def emitI2Xsignals(fogPos : Point2d, sif : double,
                   sp : double) {
  emit(new I2IFogConditionDetected => {
    fogPosition = fogPos;
    signalSourcePosition = panel.position;
    speedLimit = sif
  })

  every(1/κ seconds) [
    emit(new I2VFogConditionDetected => {
      fogPosition = fogPos;
      signalSourcePosition = panel.position;
      speedLimit = sif;
      speedLimitOnPanel = sp
    })
  ]
}
```

Listing 2 Algorithm of the smart speed limit panels with both I2I and I2V communications, using the SARL syntax

References

1. Bartok J, Bott A, Gera M (2012) Fog prediction for road traffic safety in a coastal desert region. Boundary-Layer Meteorol 145:485–506. https://doi.org/10.1007/s10546-012-9750-5
2. Bevrani K, Chung E (2012) Comparison and modification of car following models toward a more accurate microscopic simulation parameters reproduction. In: Stevens A, Chung E (eds) 19th ITS World Congress. AustriaTech, Messezentrum Wien Exhibition and Congress Center, Vienna, Austria, 19th ITS world congress, http://eprints.qut.edu.au/54588/

3. Buisson J, Galland S, Gaud N, et al (2013) Real-time collision avoidance for pedestrian and bicyclist simulation: a smooth and predictive approach. In: Yasar Auh, Knapen L (eds) 2nd International Workshop on Agent-based Mobility, Traffic and Transportation Models, Methodologies and Applications (ABMTRANS-13). Elsevier, Halifax, Nova Scotia, Canada, pp 815–820, https://doi.org/10.1016/j.procs.2013.06.108, http://www.multiagent.fr/Publication:ABMTRANS13, best Paper Award
4. Chandler RE, Herman R, Montroll EW (1958) Traffic dynamics: studies in car following. Operations Research 6(2):165–184. https://doi.org/10.1287/opre.6.2.165
5. Chang X, Li H, Qin L et al (2019) Evaluation of cooperative systems on driver behavior in heavy fog condition based on a driving simulator. Accident Analysis & Prevention 128:197–205
6. Cich G, Galland S, Knapen L et al (2017) Addressing the challenges of conservative event synchronization for the SARL agent-programming language. The 15th International Conference on Practical Applications of Agents and Multi-Agent Systems. LNCS. Springer, Portugal, pp 31–42
7. Farah H, Erkens SM, Alkim T et al (2018) Infrastructure for automated and connected driving: state of the art and future research directions. In: Meyer G, Beiker S (eds) Road Vehicle Automation 4. Springer International Publishing, Cham, pp 187–197
8. Feraud M, Galland S (2017) First comparison of SARL to other agent-programming languages and frameworks. In: International Workshop on Agent-based Modeling and Applications with SARL (SARL 2017). Elsevier, Belgium, Procedia Computer Science, https://doi.org/10.1016/j.procs.2017.05.389
9. Ferber J (1999) Multi-agent systems: an introduction to distributed artificial intelligence. Addison-Wesley
10. Galland S, Rodriguez S (2019) Semantic transformation from SARL agent-oriented statements to java object-oriented statements. International Journal of Artificial Intelligence
11. Galland S, Gaud N, Rodriguez S, et al (2010) Janus: another yet general-purpose multiagent platform. In: the 7th Agent-Oriented Software Engineering Technical Forum (TFGAOSE-10), Agent Technical Fora. Agent Technical Fora, Paris, France
12. Galland S, Gaud N, Yasar Auh, et al (2013) Simulation model of carpooling with the Janus multiagent platform. In: Yasar AuH, Knapen L (eds) 2nd International Workshop on Agent-based Mobility, Traffic and Transportation Models, Methodologies and Applications (ABMTRANS-13). Elsevier, pp 860–866, https://doi.org/10.1016/j.procs.2013.06.115
13. Galland S, Yasar Auh, Knapen L et al (2014) Simulation of carpooling agents with the Janus platform. Journal of Ubiquitous Systems & Pervasive Networks 5(2):9–15
14. Galland S, Rodriguez S, Gaud N (2017) Run-time environment for the SARL agent-programming language: the example of the Janus platform. International Journal on Future Generation Computer Systems. https://doi.org/10.1016/j.future.2017.10.020
15. Gaud N, Galland S, Hilaire V, et al (2009) An organizational platform for holonic and multiagent systems. In: Hindriks Kv, Pokahr A, Sardina S (eds) 6th International Workshop ProMAS 2008, Lecture Notes in Computer Science 5442. Springer Berlin Heidelberg, Estoril, Portugal, pp 104–119, https://doi.org/10.1007/978-3-642-03278-3_7
16. Gipps P (1981) A behavioural car-following model for computer simulation. Transportation Research Part B: Methodological 15(2):105–111
17. Grignard A, Taillandier P, Gaudou B et al (2013) GAMA 1.6: advancing the art of complex agent-based modeling and simulation. In: Boella G, Elkind E, Savarimuthu B et al (eds) PRIMA 2013: principles and practice of multi-agent systems, LNCS, vol 8291. Springer, Berlin Heidelberg, pp 117–131
18. Hao X (2017) Contribution à l'intersection coopérative: commandes longitudinale et latérale. PhD thesis, Université de Technologie de Belfort-Montbéliard, Belfort, France
19. Helly W (1961) Simulation of bottlenecks in single-lane traffic flow. In: Symposium on the Theory of Traffic Flow, pp 207–238
20. Hoogendoorn RG, Tamminga G, Hoogendoorn SP, et al (2010) Longitudinal driving behavior under adverse weather conditions: adaptation effects, model performance and freeway capacity in case of fog. In: 13th International IEEE Conference on Intelligent Transportation Systems, pp 450–455
21. Illenberger J, Flötteröd G, Nagel K (2007) Enhancing MATSim with capabilities of within-day re-planning. IEEE Intelligent Transportation Systems Conference. Seattle, WA, USA, pp 94–99
22. Lamotte O, Galland S, Contet JM, et al (2010) Submicroscopic and physics simulation of autonomous and intelligent vehicles in virtual reality. In: 2nd International Conference on Advances in System Simulation (SIMUL10)
23. Lombard A, Mualla Y, Galland S, et al (2019) Sofware architecture for drone simulation in 3D. In: First European Forum for the SARL Users and Developers (EuSarlCon 2019), Leuven, Belgium, http://www.multiagent.fr/Conferences:EuSarlCon19
24. Lopez PA, Behrisch M, Bieker-Walz L, et al (2018) Microscopic traffic simulation using sumo. In: The 21st IEEE International Conference on Intelligent Transportation Systems. IEEE, https://elib.dlr.de/124092/
25. Michel F (2007) The IRM4S model: the influence/reaction principle for multiagent based simulation. In: Proceedings of the 6th international joint conference on Autonomous agents and multiagent systems, ACM, p 133
26. Niazi M, Hussain A (2011) Agent-based computing from multi-agent systems to agent-based models: a visual survey. Scientometrics 89(2):479–499
27. Outay F, Galland S, Gaud N (2021) Simulation of connected driving in hazardous weather conditions: general and extensible multiagent architecture and models. Journal of Engineering Applications of Artificial Intelligence 104(104):412
28. Outay F, Abbas-Turki A, Galland S, et al (2022) Comparison of reaction time-based collaborative velocity control and intelligent driver model for agent-based simulation of autonomous car. In: 19th International Conference on Mobile Systems and Pervasive Computing, Acadia University and Hasselt University, Niagara Falls, Ontario, Canada
29. Rodriguez S, Gaud N, Galland S (2014) SARL: a general-purpose agent-oriented programming language. In: International Conference on Intelligent Agent Technology (IAT14). IEEE Computer Science, Warsaw, Poland, pp 103–110, https://doi.org/10.1109/WI-IAT.2014.156
30. Saunier J, Carrascosa C, Galland S, et al (2015) Agent bodies: an interface between agent and environment. In: Agent Environments for Multi-Agent Systems IV. Springer, p 25–40
31. Schakel W, Van Arem B, Bart N (2010) Effects of cooperative adaptive cruise control on traffic flow stability. In: 13th International IEEE Conference on Intelligent Transportation Systems (ITSC), pp 759–764
32. Sétra (2002) The design of interurban intersections on major roads. Tech. rep., Service d'études techniques des routes et autoroutes
33. Tan JH (2019) Impact of risk illusions on traffic flow in fog weather. Physica A: Statistical Mechanics and its Applications 525: 216–222

34. Treiber M, Hennecke A, Helbing D (2000) Congested traffic states in empirical observations and microscopic simulations. Physical Review E 62:1805–1824
35. Weyns D, Parunak HVD, Michel F et al (2005) Environment for multiagent systems state-of-the-art and research challenges. Environments for Multi-Agent Systems (E4MAS). Springer, Berlin / Heidelberg, pp 1–47