# Multi-agent cellular automaton model for traffic flow considering the heterogeneity of human delay and accelerations

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**Abstract.** We propose a multi-agent cellular automata model for analysing the traffic flow with various types of agents (drivers). Agents may differ by their vehicles' acceleration/deceleration values and the delay value of their decision-making. We propose a model in which the main parameters are chosen to reflect different types of driving. Based on valuable previous works, accurate data for possible acceleration/deceleration are used. Additionally, to accurately reflect the cars' dimensions and their limited movement in a traffic jam, a small-cell cellular automaton is used, where a set of cells represents one car. We present the results of a numerical simulation showing the influence of the main factors of the driving type on the traffic flow. Research shows that aggressive braking has a greater negative impact on traffic flow than aggressive acceleration.

**Keywords:** Cellular Automata (CA) · Traffic Flow · Agent-Based Modeling (ABM).

## 1 Introduction

There are many different models and analyses of car traffic and its effectiveness [1–4]. Regarding the microscopic approach, one can point out classical models, which include, on the one hand, time–continuous car–following model like the Intelligent Driver Model [5], and on the other hand, discrete traffic models: Nagel-Schreckenberg [6] and Chopard-Luthi-Queloz [7], where the cellular automata (CA) paradigm was applied. Although these models are relatively simple, they allow for analysis of numerous dependencies [8–15], etc. One can also identify a trend where drivers/cars are represented as agents with various abilities and driving styles [16–18]. In [17], the authors used agent-based modelling to point to on-street parking problems related to drivers' behaviours. While in [18], the authors used small–cell CA and multi-agent system to indicate the essential aspect of road traffic, which is a corridor of life.

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Among others published research, a particular number of road traffic models are oriented on the impact of vehicles' acceleration and deceleration on traffic flow. The first works assumed that the value of acceleration and deceleration is constant for all vehicles. The value 1 was suggested, understood as acceleration by one CA cell or braking by one CA cell — without distinguishing the size of the cell [8–10]. In [19], the authors performed measurements for several selected vehicles and determined the actual values of acceleration and braking. The average acceleration value was $3.22 m/s^2$, and deceleration - $8.49 m/s^2$. In [20], the authors proposed a new CA model which avoids unrealistic deceleration behaviour found in most previous CA models. They introduced a parameter $\Delta v$, according to which vehicles change their speed. It was then possible to model the traffic flow with different characteristics of acceleration and braking values, i.e. vehicles belonging to different groups (passenger cars, trucks, etc.). In the next article [21], a new simple model was proposed, in which the braking possibilities were limited (as opposed to the Nagel-Schreckenberg model, where they were unlimited [6]). Additionally, the possibility of accelerating vehicles with a certain probability was introduced (compared to the aforementioned model [6], in which only braking was based on a fixed random value). Hence, the presented fundamental diagrams had more complex than those shown in earlier works. The extension of [20] was presented in [22]. The authors gave the simulation results on a two–lane system with periodic conditions and two types of vehicles with different lengths and different limited velocities. The introduced model reproduces a realistic density dependence of the number of lane changes observed in reality and the different traffic states.

In this article, we propose a multi–agent CA model to study the impact of drivers' behaviour and their delay ratio on traffic flow. In order to obtain the possibility of indicating undesirable behaviours, we develop a CA model that allows vehicles (agents of a multi–agent system) to move with various parameters of acceleration/deceleration and a reaction distance, which is the additional gap to the preceding car that the driver would like to leave. This idea is a novelty of this work. Our model can reproduce some common characteristics of real traffic, such as the variability of acceleration and deceleration value, the density of the traffic flow, and various drivers' reactions. We hope it can help to carry out research on major negative factors for the road traffic flow.

## 2 Model

This work is based on a single–lane CA model for traffic flow, called LAI model [20] and its extension [22]. The basic model consists of a number of vehicles moving in one direction on a one-dimensional lattice, consisting of a number of cells arranged in a ring topology (Fig. 1). Hence, the number of vehicles is fixed. This allows for fixing an accurate density of traffic. Each cell is either empty or occupied by just one vehicle (or part of one vehicle) travelling with velocity $v$, which takes integer values ranging from 0 to $v_{max}$. It is assumed that vehicles move from left to right. The system evolves in time steps $\Delta t$, which is taken

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to be 1 s. In each time step, the agents decide on their velocity and then move accordingly. Each decision on the velocity is related to: a) the distance to the neighbouring vehicle and its velocity that the agent is assumed to estimate, b) the preferences of the driver, c) a small random factor.

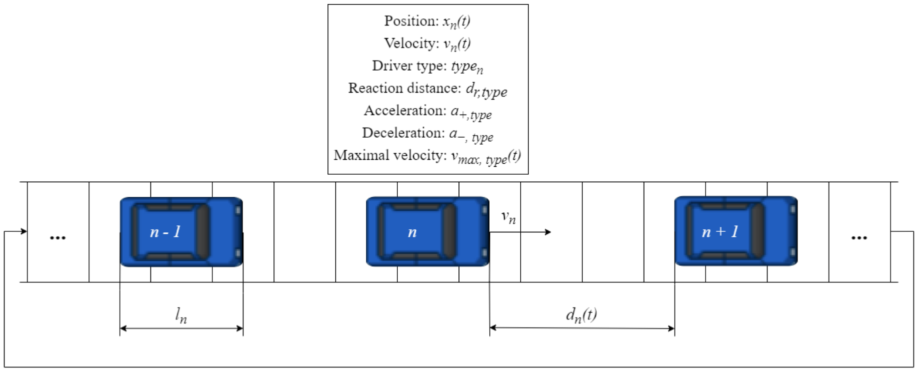

**Fig. 1.** The general approach in this study.

### 2.1 Parameters

In our multi-agent CA model, it is possible to have several types of agents. That is, several parameters that we introduce so as to model the traffic flow are based on the driver's (agent's) characteristics. We thus first introduce the driver's type. We consider five driver types in the present study.

$$type \in \{I, II, III, IV, V\}. \tag{1}$$

We then associate the following parameters to this driver's type:

$$type \mapsto (d_r, a_+, a_-, v_{max}) \tag{2}$$

where $v_{max}$ is the maximum velocity that can be attained by the driver, $a+$ and $a_-$ are the acceleration and deceleration values used by the driver, and $d_r$ is a coefficient which governs what we call the reaction distance, i.e. a distance needed by the driver to take action, which results in an additional gap between the agent and its predecessor. We assume that $d_r$ is the reaction distance when the speed is maximal, and then it is equal to the gap. For smaller velocities, the gap is defined by (7) below. This coefficient and the notion of reaction distance (or gap) are new in our study.

We also have common parameters, independent of the driver's type, which is the maximal braking deceleration

$$a_{min} = -5\,m/s^2, \tag{3}$$

and a factor $R_s \in (0,1)$, which is the probability of a random slowing down, as present in [6] and in most later works.

The values of $(d_r, a_+, a_-, v_{max})$ used for different drivers in the present paper are given in Table 1. In what follows, we may omit their dependence on the driver's type in the notation.

### 2.2 Limiting distances

With the parameters defined above, we now define the velocity changes in each step of the traffic dynamics:

$$\Delta^+ v = a_+ \cdot 1\,s, \quad \Delta^- v = a_- \cdot 1\,s, \quad \Delta_{min} v = a_{min} \cdot 1\,s. \tag{4}$$

Also, the velocity $v$ of the agent — which will be computed in each iteration on the dynamics — determines the so–called limiting distances, as in [22]):

$$d_{brake}(v) = \sum_{i=1}^{\infty} \max\left(v + i\Delta_{min} v, 0\right) \cdot 1s \tag{5}$$

$$d_{safe}(v) = v \cdot 1s + d_{brake}(v). \tag{6}$$

Here, $d_{brake}(v)$ is the braking distance, i.e. the distance needed to reduce the velocity to 0, when using the maximal deceleration $a_{min}$. The safe distance $d_{safe}(v)$ is the distance covered in 1 s with velocity $v$ plus the braking distance. Note that the sum in (5) is actually finite and that the formula coincides with [22, (5)]. Also, our (6) coincides with [22, (4)] (denoted by $d_f$ there).

Our new reaction distance (or gap) $g$ is defined as follows: and for smaller velocities, decreases linearly:

$$(v, type) \mapsto g = d_r \frac{v}{v_{max}} \tag{7}$$

i.e., the gap is equal to $d_r$ when the velocity $v$ is maximal, and decreases linearly to zero for smaller velocities. This reaction distance may also be interpreted as the speed of the driver's reaction.

As for the parameters, we may omit the dependence of $g$ on the driver's type, and write just $g(v)$, by the sake of simplicity of notation.

### 2.3 Dynamics

Our system consists of $N$ vehicles evolving in time steps $t = 0, 1, \ldots$. In each time moment $t$ and for each vehicle $n$ we store:

$$(x_n(t), d_n(t), v_n(t), l_n, type_n), \tag{8}$$

where: $x_n(t)$ is the vehicle's $n$ position, $d_n(t) = x_{n+1}(t) - l_{n+1} - x_n(t)$ is its distance to the preceding one, $v_n(t)$ its velocity at time $t$. The static variables $l_n, type_n$ are the length and type of the vehicle $n$. Let us describe the evolution from time step $t$ to $t+1$.

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*Dynamic safe distances.* We first define, as a function of $v_n(t)$, the following additional distances, which are going to be crucial for the agent's decision on its speed in the next time moment:

$$(v_n(t), type) \mapsto \begin{cases} d_{-,n}(t) = d_{safe}(v_n(t) + \Delta^- v) + g(v_n) \\ d_{0,n}(t) = d_{safe}(v_n(t)) + g(v_n) \\ d_{+,n}(t) = d_{safe}(v_n(t) + \Delta^+ v) + g(v_n) \end{cases}, \tag{9}$$

where $d_{safe}$ and $g$ are defined in (6)–(7). Thus, $d_{0,n}(t)$ is the sum of the safe distance for the actual velocity, and of the reaction gap for the same velocity; $d_{-,n}(t)$ is the sum of a distance which is safe if the agent decreases its velocity, and of the reaction gap for the actual velocity; $d_{+,n}(t)$ is the sum of a distance which is safe if the agent increases its velocity, and of the reaction gap for the actual velocity. One may also consider a model with the same velocities in both components of the sum; however, this would demand a slight modification of the gap definition (7). It is a matter of choice and is not crucial for the present study.

In the same way, we define the dynamic distances, which take additionally into account the velocity of the preceding vehicle, that the driver of the vehicle $n$ is assumed to estimate (see [22, (1)-(3)]):

$$D_{*,n}(t) = \max(d_{*,n}(v_n(t)) - d_{brake}(v_{n+1}(t)), 0) \tag{10}$$

where $* \in \{-, 0, +\}$.

*Randomness.* In each time step, we take a random number $r(t) \in [0, 1]$.

*The decision on the velocity change.* The determination of $v_n(t+1)$, follows the main lines of [22, (S3)]. However, we do not use the random factor for acceleration, which the authors introduce there, as we do not want to overload the model with randomness and instead determine the influence of various drivers' behaviour on the dynamics.

$$v_n(t+1) = \begin{cases} \min\left(v_n(t) + \Delta^+ v; v_{max}\right) & \text{if } d_n(t) \geq D_{+,n}(t) \\ & \text{(accelaration)} \\ v_n(t) & \text{if } \big(d_n(t) \in [D_{0,n}, D_{+,n}(t)) \text{ or } v_n(t) = v_{max}\big) \\ & \quad \text{and } r(t) > R_s \\ & \text{(random keeping the same speed)} \\ \max\left(v_n(t) + \Delta^- v; 0\right) & \text{if } \big(d_n(t) \in [D_{0,n}, D_{+,n}(t)) \text{ or } v_n(t) = v_{max}\big) \\ & \quad \text{and } r(t) \leq R_s \\ & \text{(random slowing down)} \\ \max\left(v_n(t) + \Delta^- v; 0\right) & \text{if } d_n(t) \in [D_{-,n}, D_{0,n}(t)) \\ & \text{(braking)} \\ \max\left(v_n(t) + \Delta_{min} v; 0\right) & \text{if } d_n(t) < D_{-,n} \\ & \text{(emergency braking)} \end{cases} \tag{11}$$

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*Movement.* Once the decision on the speed is taken, the vehicles move accordingly; their velocities and the distances between them are updated:

$$x_n(t+1) = x_n(t) + v_n(t+1), \tag{12}$$

$$d_n(t+1) = x_{n+1}(t+1) - l_{n+1} - x_n(t+1). \tag{13}$$

### 2.4 Agents behaviour

We give in Table 1 the five types of agents, their values of acceleration and deceleration and the gap factor parameter $d_r$, which determines the gap to the previous car according to (7).

**Table 1.** Parameter settings for different agent types

| Agent type | Gap ($d_r$) | Acceleration ($a_+$) | Deceleration ($a_-$) |
|---|---|---|---|
| I | (0;5;10) | slow (1) | slow (-1) |
| II | (0;5;10) | moderate (2) | moderate (-2) |
| III | (0;5;10) | aggressive (4) | aggressive (-4) |
| IV | (0;5;10) | aggressive (4) | slow (-1) |
| V | (0;5;10) | slow (1) | aggressive (-4) |

Agents of type I and II are the most standard, considered in most of the cited research. Their specificity — the value of acceleration and deceleration, and the gap (here $d_r = 0$) — is taken from other publications: [20, 19, 23]. Agents of types III, IV and V correspond to the aggressive driving style. Agent III is totally aggressive; the acceleration and deceleration values are almost the highest as for real data for various cars' descriptions [19]. The other agents (type IV and V) are defined in view of determining which one of the factors — the value of acceleration or braking — is more significant in maintaining traffic flow. Agent of type IV is aggressive in the context of acceleration, while Agent of type V is aggressive in the context of braking.

## 3 Numerical results

Numerical tests were performed for one type of vehicle with a length of 8 CA cells, which is about 5 meters. The length of each cell is set to 0.625 m. A small CA cell and mapping a car on a few CA cells allow for smaller vehicle movements, which is essential in the case of such research, in which small shifts make a big difference. The system size is assumed to be 3200 segments, corresponding to an actual road length of around 2 km. One time step approximately equals 1 s in real-time. Thus, the maximum velocity in the model is $v_{max} = 24$, which corresponds to 54 km/h in urban traffic. The above values (CA cell size, 1 s of time step) allowed us to obtain the integer values of real velocity (ie. $v = 4$

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corresponds to 9 km/h, $v = 8 - 18$ km/h, etc.). All charts with fundamental diagrams show the results of the arithmetic mean of 100 simulations for each density. Each simulation lasted 2,200 iterations. To analyze the results, the first 200 time steps of the simulation are discarded to let short-lived states die out and reach the system's steady state.

We used a PC with AMD Ryzen 9 (5950X), 3.40 GHz, 32GB DDR4 3200MHz CL16 dual-channel, working under MS Windows 11 (64-bits) for all simulations.

The first study shows the impact of drivers' behaviours on the traffic flow for left, right and both lanes, respectively (Fig. 2). In this study, the parameter $d_r$ is constant and equals 0 for each agent type. Each line presents a traffic flow for a 100% of the certain type of agent (Table 1) and road occupation. As the chart presents, each form of aggressiveness reduces the flow of vehicles. Moreover, the non-trivial conclusion is that aggressiveness in braking is more destructive to the traffic flow than aggressiveness in acceleration. Agents type III and V, with the highest deceleration value, make traffic flow the least efficient, while agents type IV slightly reduce it. In addition, it is worth noting the change in the shape of the curve representing the road occupancy for agents type V. Its slope changes sharply in the range of road occupancy from 40% to 70%. This change requires further analysis in future studies.

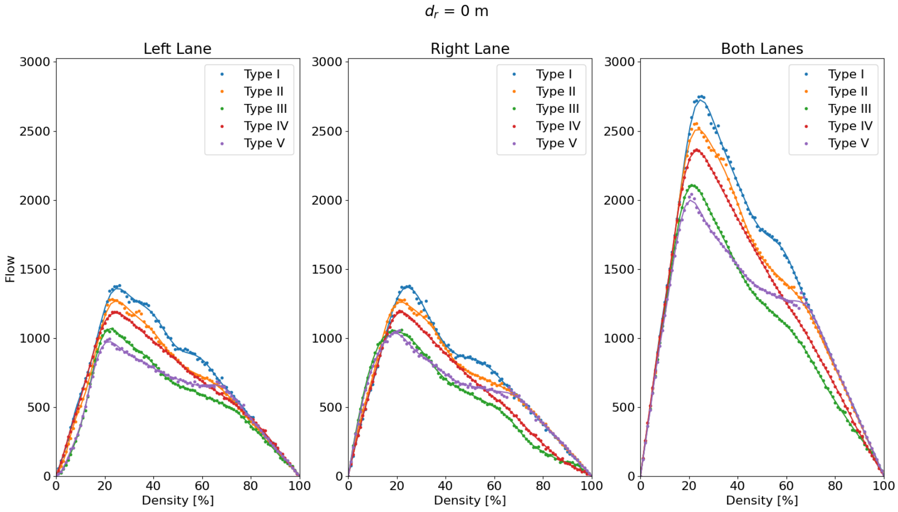

**Fig. 2.** Fundamental diagram of the presented model for various types of drivers, and $d_r = 0$.

The space-time plots were additionally generated for this simulation study (Fig. 3). We mark in red the moment when the lane changes occur. In this way, the specificity of the behaviour of individual agents is revealed. Agents III and V

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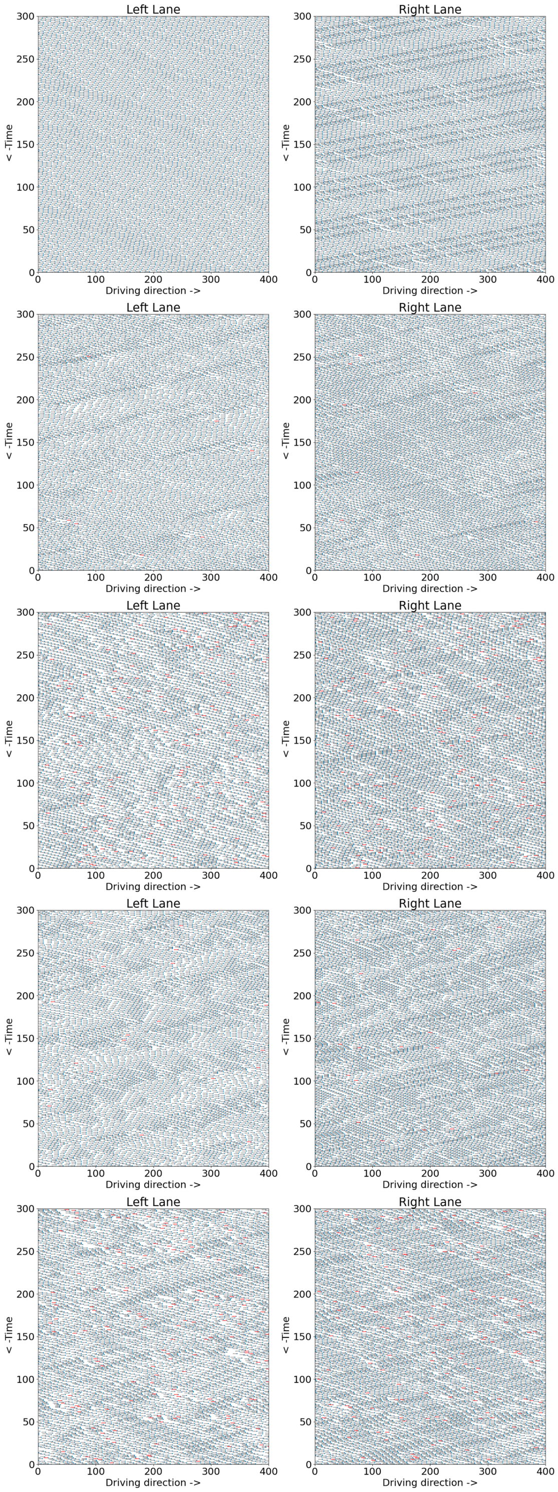

**Fig. 3.** The space–time plots of the present model, where $d_r = 0$. Each line presents a diagram for the left and right lanes. The next lines present the results for agents I-V (from the top). The vehicles move from the left to the right, and the vertical direction (down) of each graph means the next iterations.

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show up a higher frequency of changing lanes, which results in numerous changes in the speed of other vehicles and consequently reduces the total traffic flow.

Furthermore, Fig. 2 reflects the most common approach when the reaction distance (the gap between the vehicles) is 0: $d_r = 0$. Our aim is to prepare a CA model to study the effect of the extra gap to the previous car on traffic flow. For that reason, based on the CA model extension, the next simulations have been done, and the results are presented as fundamental diagrams (Figs. 4 and 5). The next simulation study was based on all the above–defined agent types, but all of them use the privilege to have a distance to the previous car set to 5 ($d_r = 5$). This value is reduced as the vehicle's speed decreases, as it was described in section 2.1.

The possibility of an additional distance to the vehicle ahead revealed a smaller range of maximum traffic flow value in relation to individual agents, about 25% (Fig. 4) relative to 37% (Fig. 2). In addition, the flow characteristics of traffic have changed. Increasing the gap caused disturbances in the trends in the area of road occupation oscillating in the range of about 65% to 95%. In the first study, agents type III generated the lowest ratio of traffic flow, while in the second simulation, agents type IV generated the lowest throughput.

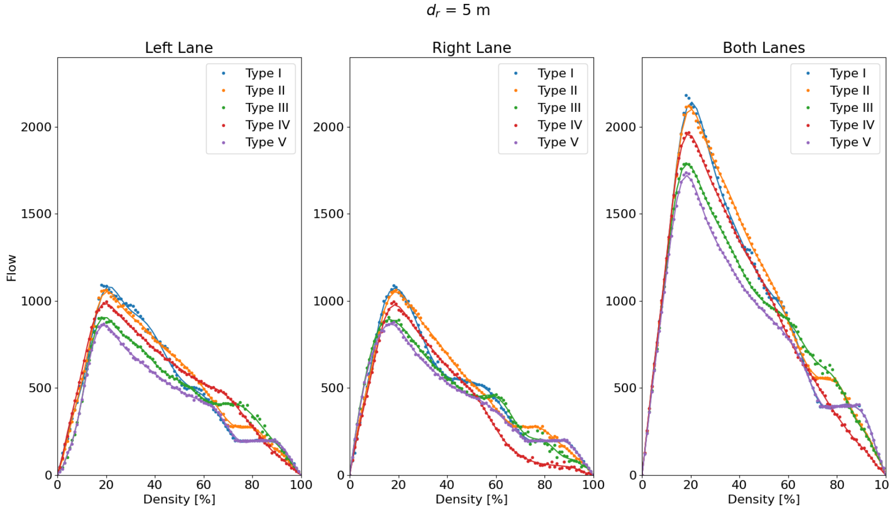

**Fig. 4.** Fundamental diagram of the presented model for various types of drivers, and $d_r = 5$.

In the next study, we increased the value of parameter $d_r$, which now equals 10. The results are presented in Fig. 5. Traffic flow decreased by about 48% relative to agent type I and about 33% relative to agent type V in the study with parameter $d_r = 0$. While the relationship between this study and the study

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with $d_r = 5$ is a decrease of about 19% and about 13%, relative to agents type I and V.

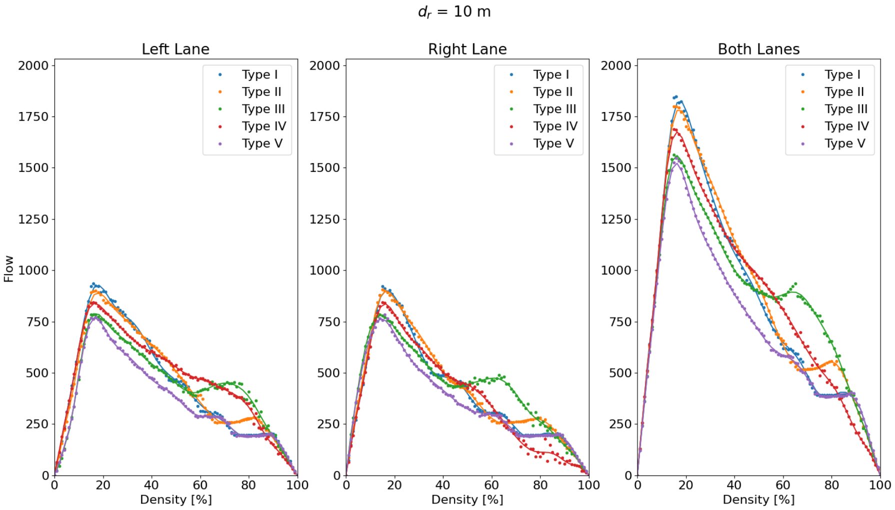

**Fig. 5.** Fundamental diagram of the presented model for various types of drivers, and $d_r = 10$.

The space-time plots were also generated for this simulation study (Fig. 6). Again, agents III and V have increased lane change variability. However, it is smaller than when the parameter $d_r = 0$, which means that the value of this parameter is important for the overall traffic flow. The increased distance between vehicles has an impact on traffic stability.

In addition, when the distance between the vehicles was increased, there were disturbances in traffic flow for agents type I, II, III and V, in the range of the road occupancy from about 60% to about 85%. This applies to disturbances on each lane separately and on both lanes together. The results show a situation where slow acceleration and braking generate an advantage in the form of a fluent going of the whole stream of vehicles, even though for the road occupancy above 60% traffic flow is lower for agents type III, and for the road occupancy from about 80% for other agent types, for $d_r = 10$ (Fig. 5).

So as to present the difference between agent types more clearly, fundamental diagrams for various values of $d_r$ parameter are given in Figs. 7, 8.

## 4 Conclusion

This paper presents a multi-agent CA model to evaluate how heterogeneity in road traffic caused by different driver profiles affects traffic dynamics. Drivers'

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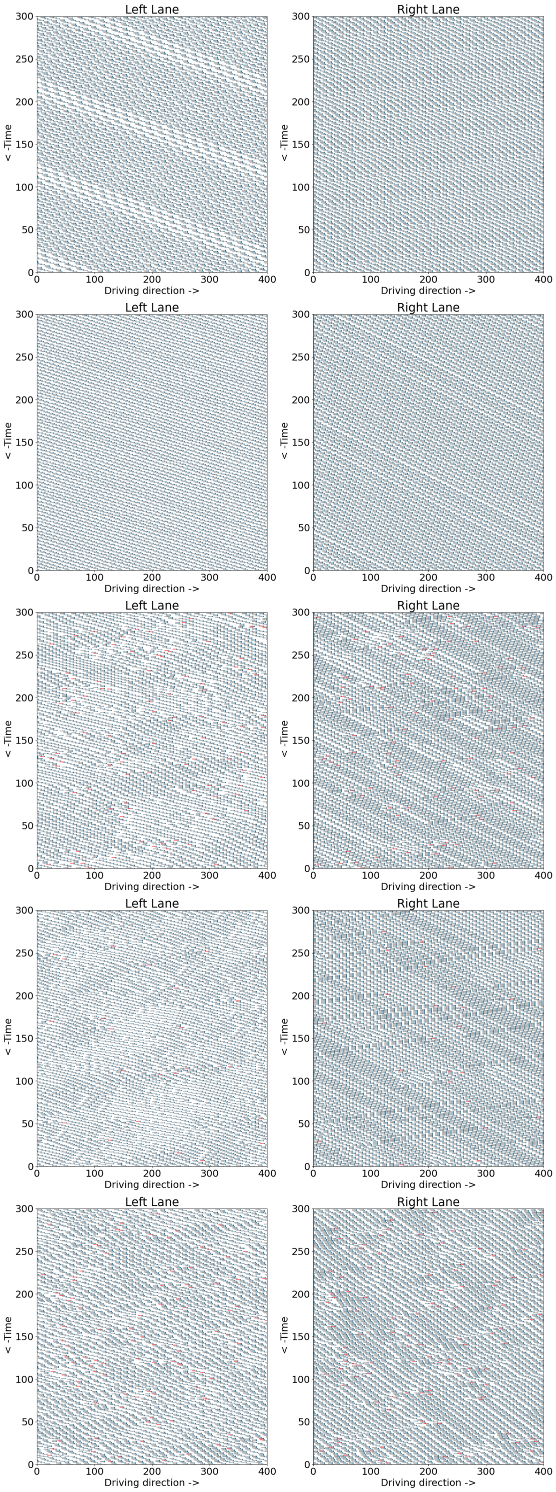

**Fig. 6.** The space–time plots of the present model, where $d_r = 10$. Each line presents a diagram for the left and right lanes. The next lines present the results for agents I-V (from the top).

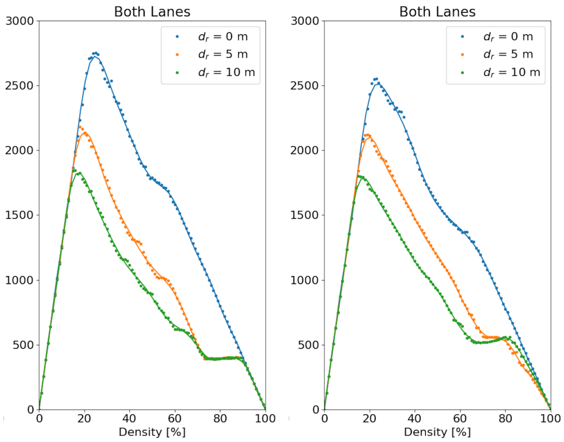

**Fig. 7.** The comparison of fundamental diagrams for various values of $d_r$ for agent type I and II (from left).

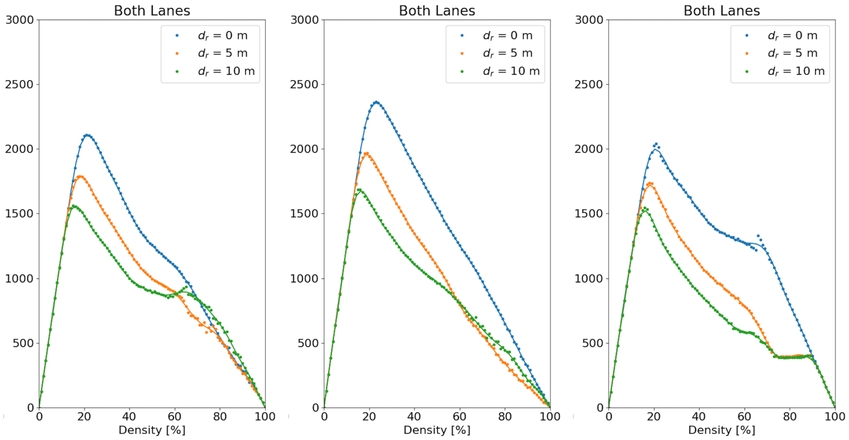

**Fig. 8.** The comparison of fundamental diagrams for various values of $d_r$ for agents with any kind of aggressiveness (type III, IV, and V - from left).

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profiles, defined by varying acceleration and decelerations policies and the redundant gap to other road users, are difficult to be observed in standard road measurements and can only be evaluated through computational simulations. Therefore, five types of drivers were defined, and the differences between them were shown based on fundamental and space-time diagrams. Aggressive braking has been shown to be more destructive to traffic flow than aggressive acceleration. In addition, the model uses the representation of a single vehicle as a set of several CA cells, which allows for a more realistic representation of urban speeds and parameters considered in this article (acceleration and deceleration values and the distance between vehicles).

Finally, the proposed model preserves computational simplicity, and its rules make it possible to use parallel computing. This critical feature of the CA models is therefore held.

The plan for future research is to examine the effect of the distance to the preceding vehicle in relation to the agent types. This parameter turned out to be an important factor causing a change in the characteristics of traffic flow, especially when road occupancy increases. This knowledge is essential from the point of view of designers of algorithms controlling autonomous vehicles.

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## References

1. Macioszek, E.: Analysis of driver behaviour at roundabouts in tokyo and the tokyo surroundings. Volume 1083 AISC of Advances in Intelligent Systems and Computing. (2020)
2. Sierpiński, G.: Revision of the Modal Split of Traffic Model. Volume 395 CCIS of Communications in Computer and Information Science. (2013)
3. Macioszek, E.: Models of critical gaps and follow-up headways for turbo roundabouts. Volume 52 of Lecture Notes in Networks and Systems. (2019)
4. Macioszek, E., Sierpiński, G., Czapkowski, L.: Methods of modeling the bicycle traffic flows on the roundabouts. Volume 104 CCIS of Communications in Computer and Information Science. (2010)
5. Treiber, M., Hennecke, A., Helbing, D.: Congested Traffic States in Empirical Observations and Microscopic Simulations. Phys. Rev. E **62** (2000) 1805–1824
6. Nagel, K., Schreckenberg, M.: A cellular automaton model for freeway traffic. J. Phys. I France. **2** (1992)
7. Chopard, B., Luthi, P.O., Queloz, P.A.: Cellular automata model of car traffic in a two-dimensional street network. Journal of Physics A Mathematical General **29** (1996) 2325–2336

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DOI: 10.1007/978-3-031-35995-8_38

8. Schadschneider, A., Schreckenberg, M.: Traffic flow models with 'slow-to-start'rules. Annalen der Physik **509** (1997) 541–551
9. Nagel, K., Wolf, D.E., Wagner, P., Simon, P.: Two-lane traffic rules for cellular automata: A systematic approach. Physical Review E **58** (1998) 1425
10. Rickert, M., Nagel, K., Schreckenberg, M., Latour, A.: Two lane traffic simulations using cellular automata. Physica A: Statistical Mechanics and its Applications **231** (1996) 534–550
11. Liu, M., Shi, J.: A cellular automata traffic flow model combined with a bp neural network based microscopic lane changing decision model. Journal of Intelligent Transportation Systems **23** (2019) 309–318
12. Małecki, K., Gabryś, M.: The computer simulation of cellular automata traffic model with the consideration of vehicle-to-infrastructure communication technology. Simulation **96** (2020) 911–923
13. Wójtowicz, J., Wadowski, I., Dyrda, B., Gwizdałła, T.M.: Traffic on small grids and the ramp problem. In: Cellular Automata: 13th International Conference on Cellular Automata for Research and Industry, ACRI 2018, Como, Italy, September 17–21, 2018, Proceedings 13, Springer (2018) 196–206
14. Małecki, K.: The use of heterogeneous cellular automata to study the capacity of the roundabout. In Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M., eds.: Artificial Intelligence and Soft Computing, Cham, Springer International Publishing (2017) 308–317
15. Iwan, S., Małecki, K.: Utilization of cellular automata for analysis of the efficiency of urban freight transport measures based on loading/unloading bays example. Transportation research procedia **25** (2017) 1021–1035
16. Chmielewska, M., Kotlarz, M., Was, J.: Computer simulation of traffic flow based on cellular automata and multi-agent system. In Wyrzykowski, R., Deelman, E., Dongarra, J., Karczewski, K., Kitowski, J., Wiatr, K., eds.: Parallel Processing and Applied Mathematics, Cham, Springer International Publishing (2016) 517–527
17. Małecki, K.: A computer simulation of traffic flow with on-street parking and drivers' behaviour based on cellular automata and a multi-agent system. Journal of computational science **28** (2018) 32–42
18. Małecki, K., Kamiński, M., Was, J.: A multi-cell cellular automata model of traffic flow with emergency vehicles: Effect of a corridor of life and drivers' behaviour. Journal of Computational Science **61** (2022) 101628
19. Shang, H.Y., Peng, Y.: A new three-step cellular automaton model considering a realistic driving decision. Journal of Statistical Mechanics: Theory and Experiment **2012** (2012) P10001
20. Lárraga, M.E., Alvarez-Icaza, L.: Cellular automaton model for traffic flow based on safe driving policies and human reactions. Physica A: Statistical Mechanics and its Applications **389** (2010) 5425–5438
21. Chmura, T., Herz, B., Knorr, F., Pitz, T., Schreckenberg, M.: A simple stochastic cellular automaton for synchronized traffic flow. Physica A: Statistical Mechanics and its Applications **405** (2014) 332–337
22. GUZMÁN, H., Larraga, M.E., Alvarez-Icaza, L., et al.: A two lanes cellular automata model for traffic flow considering realistic driving decisions. Journal of cellular automata **10** (2015)
23. Li, Z.H., Zheng, S.T., Jiang, R., Tian, J.F., Zhu, K.X., Di Pace, R.: Empirical and simulation study on traffic oscillation characteristic using floating car data. Physica A: Statistical Mechanics and its Applications **605** (2022) 127973

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