A multi-cell cellular automata model of traffic flow with emergency vehicles: effect of a corridor of life

Krzysztof Małecki[1][0000−0002−8687−1119], Marek Kamiński[2], and Jarosław Was[3][0000−0003−2964−745X]

[1] West Pomeranian University of Technology, Zołnierska 52 Str., Szczecin, Poland
kmalecki@wi.zut.edu.pl
[2] Profi-Data Sp. z o.o., Milczańska 30A Str., Szczecin, Poland
marek.kaminski.93@gmail.com
[3] AGH University of Science and Technology, Mickiewicza 30 Str., Krakow, Poland
jarek@agh.edu.pl

Abstract. There are various macroscopic and microscopic road traffic models that allow traffic flow analysis. However, it should be emphasized that standard traffic flow models do not include emergency vehicle traffic. We propose a multi-agent microscopic model for analyzing traffic flow of emergency vehicles with some limitations to the distance between vehicles and their proper distribution (corridor of life) to leave free passage for a privileged vehicle. Real data was used to calibrate and validate the model. Our simulation studies show the importance of certain aspects of road traffic (distance between vehicles, corridor of life, size and type of roadside, friction conflict, etc.) in order to increase / decrease the traffic flow in the aspect of an approaching of emergency vehicle.

Keywords: Agent-Based Modeling (ABM) · Cellular Automata (CA) · Traffic Modeling · Emergency Vehicles · Friction Conflict.

1 Introduction

The rapid arrival of emergency services such as the fire brigade, ambulance or police to the places of dangerous incidents is crucial and often seconds decide about the life or health of people. In the urban areas, but also on highways or tunnels, traffic jams and high traffic density often occur. In such situations, leaving the corridor of life is extremely important behavior.

There are many different models of car traffic. Regarding microscopic approach one can point out classical models, including on the one hand, continuous ones like Intelligent Driver Model - a time-continuous car-following model [1]. On the other hand there are discrete models like classical ones: Nagel-Schreckenberg model [2] and Chopard- Luthi-Queloz traffic model [3], where CA paradigm was applied. Although these models are relatively simple they allow for analysis of different relationships [4–8], etc. One can also identify a trend where drivers/cars are represented as agents and their possess different abilities [9].

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77961-0_4

The emergency cars simulation was performed in [10]. The author confirmed that the mean speed of the emergency car and its arrival time all depend enormously on the cars density, the route length of the emergency vehicle and the turn capability of the cars. However, following the [11] one can point that the majority of studies based on emergency cars have deals with such problems as: emergency vehicles location problem [12], emergency vehicles dispatching problem [13], and emergency vehicles routing problem which consists of finding a shortest (fastest) path from one location to another [14]. The results of prediction of travel time of the priority vehicles are also available [15, 16].

In this article, the authors proposed a multi-agent multi-cell CA model to study the impact of drivers' behavior on the road on the time of an emergency vehicle moving. The novelty of this work is to develop a CA model that allows vehicles to move sideways. This was achieved by mapping each lane of the road as a grid of small cells that enables this effect. It should be stressed that standard traffic flow models do not take into account the movement of emergency vehicles, however it is highly required to consider such microscopic models in process of stationing deployment of emergency vehicles.

2 Proposed model

2.1 Road structure, types of vehicles and real data

A one-way two-lane road has been mapped. Vehicles move in two directions - forward and sideways. To get high accuracy simulation, the road was divided into many small cells. The grid of a CA consists of two lanes of road divided into cells of 1 m long and 0.25 m wide (Table 1).

Table 1. Road width (according to regulations in Poland [17].

Road width [m]	Road width [cells]	Minimum roadside width [cells]
2.5	10	10
3.0	12	6
3.5	14	2
3.75	15	0

To avoid a situation in which the emergency vehicle traffic would be permanently blocked due to insufficient road width, a roadside was used. The size of the roadside is adapted to the width of the road so that the total width of the road is at least equal to the sum of the width of two trucks and a firefighter car. In the developed system, however, it is possible to widen the roadside in the range of 1 to 5 CA cells on one side of the road.

A few type of vehicles are considered (Table 2). The developed model uses small CA cells to allow the vehicles to move sideways. However, the larger the vehicle is, the more difficult it is to maneuver. Therefore, a number of empirical

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77961-0_4

Table 2. Types of vehicles (based on real sizes taken from vehicles' catalog).

Type of vehicle	Size (length; width) [m]	Size (length; width) [CA cells]
Ambulance	6; 2	6; 8
Firefighter car	9; 2.5	9; 10
Truck	18; 2.5	18; 10
Small car	3; 1.5	3; 6
Medium car	4; 1.75	4; 7
Big car / Bus	5; 2	5; 8

measurements were carried out, on the basis of which the possible maximum lateral shift after a certain distance forward was determined (Fig. 1).

Fig. 1. Some examples of empirical data taken for different types of vehicles.

2.2 The corridor of life

The so-called corridor of life is a free space on the road created for emergency vehicles, by stopping vehicles standing in a traffic jam at the edge of the road. Such solution has been implemented in the developed model (Fig. 2). When there is a situation that the vehicle is forced to reduce its speed, e.g. due to coming to a traffic jam, it will start the descent towards the appropriate edge of the road, thus creating a free passage in the middle of the road. If curb is chosen as the roadside type, then the vehicles will be as close as possible to it first. However, if an emergency vehicle appears and it does not have enough space to continue its travel, then the other vehicles will start to enter the curb at a speed of 1 cell / iteration.

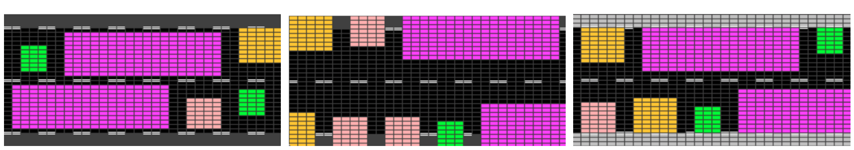

Fig. 2. A traffic jam without a corridor of life (top), with corridor of life (in the middle), and with corridor of life on the road with curbs (bottom)

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77961-0_4

2.3 Safe distance between cars and the friction conflict

It is good practice to maintain such a distance from the vehicle in front of you that, in the event of an unexpected traffic situation, ensure sufficient time and room to react. In the system the safe distance can have values from 0 to 5 CA cells (from 0 to 5 m) and it is one of observed parameter.

In a situation where cars in traffic jams leave a little space for an emergency vehicle, the driver of such vehicle cannot drive at high speed for fear of collision with other vehicles. An emergency vehicle must significantly reduce the speed of the journey. This situation is referred to as a friction conflict, i.e. an emergency vehicle moves between other vehicles, from which it will not be separated even by a single CA cell of free space. Based on observation, we assume that then the maximum speed is automatically limited to 5 cells/iteration (about 18 km/h).

2.4 The rules of traffic movement

The rules of emergency vehicles In order to properly describe a movement of each type of analysed vehicle, a set of possible actions should be established.

1. Acceleration: $v_i(t) < v_{max} \rightarrow v_i(t+1) = v_i(t) + 1$, where $v_i(t)$ - speed of vehicle in i-cell in time t, v_{max} - the maximum possible speed.
2. The best route - specification of the side shift value (s_{side}), according to the developed algorithm.
3. Breaking - here are two stages:
   (a) based on step2 with formula as follows:

$$s_{side} \neq 0 \rightarrow v_i(t) = \begin{cases} 0 & \text{if } s = 0 \\ max(1, min(s, \sqrt{2sa_b})) & \text{if } s > 0 \end{cases}, \tag{1}$$

   where $v_i(t)$ - speed of vehicle in i-cell in time t, s - the distance to the nearest obstacle, a_b - a traffic delay factor, s_{side} - the value of side shift.
   (b) The second stage only occurs when the passage is too tight and there is so-called a friction conflict, this is illustrated by the following relationship: $v_i(t) > 5 \rightarrow v_i(t+1) = 5$
4. Identification of the area in which the emergency vehicle's signals are 'heard' or 'visible'.
5. Shift - after completing all previous steps, the vehicle already has a new speed specified and must change its position at $t + 1$ according to its value.

The rules of classical vehicles The subsequent states of classical vehicles are determined as follows:

1. Acceleration: $v_i(t) < v_{max} \rightarrow v_i(t+1) = v_i(t) + 1$, where $v_i(t)$ - speed of vehicle in i-cell in time t, v_{max} - the maximum possible speed.

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77961-0_4

2. Braking - based on the distance of the car to the nearest vehicle and is expressed by the following formula:

$$v_i(t) = \begin{cases} 0 & \text{if } s = 0 \\ max(1, min(s, \sqrt{2sa_b})) & \text{if } s > 0 \end{cases}, \tag{2}$$

   where $v_i(t)$ - speed of vehicle in i-cell in time t, s - the distance to the nearest obstacle, a_b - a traffic delay factor.
3. If the emergency vehicle is approaching, then perform the first and second steps again.
4. Random event - the simulation of unexpected events on the road (pedestrian intrusion, sudden braking in front of an obstacle, etc.). This step is expressed by the following formula: $v_i(t) > 0 \wedge P(t) < p \rightarrow v_i(t+1) = v_i(t) - 1$, where $v_i(t)$ - speed of vehicle in i-cell in time t, $P(t)$ - the value of the random variable at time t, p - the probability of a random event.
5. If it is necessary, try to turn off the road to make place for an emergency vehicle.
6. Consider if being in the signal area of the emergency vehicle
7. Shift - after completing all previous steps, the vehicle already has a new speed specified and must change its position at $t + 1$ according to its value.

3 Results

Numerical tests were conducted for two types of emergency vehicles - ambulance and fire brigade. The system was upgraded every 1 second. The results are the arithmetic mean of 100 simulations and show the delay of the emergency vehicle in relation to the time that this vehicle could pass the road while it was traveling with the maximum speed allowed. The road density was assumed in the range from 10% to 20% with a 0.2% step and the distance between vehicles standing in the traffic jam in the range from 0 m to 5 m.

The analysis shows the correlation between the value of delay and the distance between standing vehicles (Fig. 3). The greater the distance left between the vehicles is, the faster the emergency vehicle is able to cross the road with traffic jam. In addition, narrow roads with a single lane width of 2.5 m or 3.0 m generate a much greater delay compared to roads with a single lane width of above 3.5 m. In contrast to the charts for the ambulance, the increase of road density causes a worsening of the travel time, no matter how big the distance between standing cars is. In addition, for lanes with a width of 3 m and 3.5 m, the delay is close to the value of the ambulance delay on the road with a lane width of 2.5 m. This is related to the larger dimensions of the fire brigade vehicle in relation to the ambulance. In the case of a vehicle as large as the fire brigade, the benefits resulting from the increased road width seem to be noticeable only for a road with a width of 3.75 m.

The simulation results show that the lack of free space between vehicles standing in a traffic jam makes it impossible to perform maneuvers to give way to an emergency vehicle. This takes on special importance when the emergency

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77961-0_4

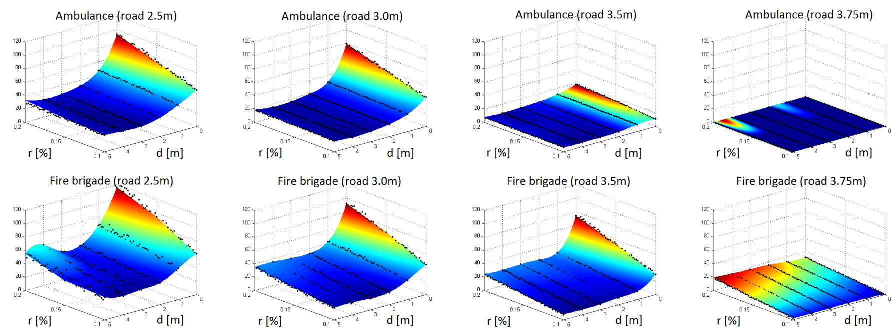

Fig. 3. Ambulance (the first row) and fire brigade (the second row) delays on the road with two lanes (a) 2.5m wide each, (b) 3.0m wide each, (c) 3.5m wide each, and (d) 3.75m wide each, depending on the road density - r and distance between vehicles - d.

vehicle is a fire vehicle, i.e. a vehicle with a much larger size than a police car or ambulance. The biggest differences are noticeable in the vicinity of 20% of the density and distance at the level of 0 m. It can be concluded that in a certain range of values, the negative effect of compaction growth can be offset by the increased distance between vehicles. In this case, it can be assumed that if drivers observe increased traffic flow on the road, they should keep a greater distance between themselves. In the analyzed cases, the fire brigade vehicle again had a greater delay in transit due to the increased its dimensions and the occurring friction conflict.

4 Conclusions

The most important conclusions from the work carried out can be formulated as follows: (1) The proposed microscopic approach in traffic modeling, taking into account the detailed geometry of the roads and the specificity of drivers' behavior in a given area, is useful in the process of stationing deployment of emergency vehicles. (2) The use of small cells of cellular automaton enables efficient modeling of lateral shifts and frictional conflicts. (3) Leaving a greater distance between vehicles immobilized in a traffic jam has a positive effect on better maneuverability and thus less delay in the passage of a priority vehicle. (4) Potential friction conflicts can be predicted on the basis of maps. Geometry of particular roads, as well as behaviors of other road users are crucial factors in planning the arrival time of priority vehicles on a specified route.

5 Acknowledgements

The authors would like to thank Daniel Budka for helping in the field experiments and MiraTrans Transport i Spedycja Sp. z o.o. for lending a truck with a driver to carry out measurements in order to calibrate the developed model.

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77961-0_4

References

1. Treiber, M., Hennecke, A., Helbing, D.: Congested Traffic States in Empirical Observations and Microscopic Simulations. Phys. Rev. E **62** (2000) 1805–1824
2. Nagel, K., Schreckenberg, M.: A cellular automaton model for freeway traffic. J. Phys. I France. **2** (1992)
3. 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
4. Schadschneider, A., Schreckenberg, M.: Traffic flow models with 'slow-to-start'rules. Annalen der Physik **509** (1997) 541–551
5. 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
6. 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
7. 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
8. 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
9. 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
10. Moussa, N.: Modeling evacuation of emergency vehicles by cellular automata models. International Journal of Modern Physics C **19** (2008) 947–956
11. Fancello, G., Mancini, S., Pani, C., Fadda, P.: An emergency vehicles allocation model for major industrial disasters. Transportation Research Procedia **25** (2017) 1164 – 1179 World Conference on Transport Research - WCTR 2016 Shanghai. 10-15 July 2016.
12. Bélanger, V., Ruiz, A., Soriano, P.: Recent optimization models and trends in location, relocation, and dispatching of emergency medical vehicles. European Journal of Operational Research **272** (2019) 1–23
13. Sudtachat, K., Mayorga, M.E., Chanta, S., Albert, L.A.: Joint relocation and districting using a nested compliance model for ems systems. Computers and Industrial Engineering **142** (2020)
14. Zhao, H., Li, J., Nie, C.: Cellular automaton models for traffic flow considering opposite driving of an emergency vehicle. International Journal of Modern Physics C **26** (2015)
15. Piórkowski, A.: Construction of a dynamic arrival time coverage map for emergency medical services. Open Geosciences **10(1)** (2018) 167–173
16. Płokita, I., Piórkowski, A., Lupa, M.: Comparative analysis of algorithms for calculating arrival times of emergency vehicles. Geoinformatica Polonica **2016** (2016)
17. Dz, U.: Announcement of the Minister of Infrastructure and Construction of the Republic of Poland of 23 december 2015 on The Technical Conditions to be met by Public Roads. **124** (2015) 9–10

ICCS Camera Ready Version 2021
To cite this paper please use the final published version:
DOI: 10.1007/978-3-030-77961-0_4